2019

Comparative assessment of the economic and environmental impacts of food waste fermentation on value-added products

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by

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A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Agricultural and Biosystems Engineering

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Ames, Iowa

2019

DEDICATION

To my husband Wan Mohd Saifudin W.Ibrahim and my children, Wan Saydatul Safiyya, Wan Umar Fawwaz and Wan Naufal Amsyar,

From umi with love.

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NOMENCLATURE

FW	Food waste
CHP	Combined heat power
Mg	Metric tons
MC	Moisture content
rpm	revolutions per minutes
GHG	Greenhouse gasses
IRR	Internal rate of return
TEA	Techno-economic analysis
LCA	Life cycle assessment

ACKNOWLEDGMENTS

Foremost, I would like to express my sincere gratitude to my committee chair Dr. Kurt A. Rosentrater and my committee members, Dr. Zhiyou Wen, Dr. Thomas J. Brumm, Dr. Chenxu Yu and Dr. Gretchen A. Mosher for the continuous support and guidance throughout my Ph.D. study and research. I am blessed with all the suggestions and comments from the experienced person at Iowa State University.

A special thanks to my family; Mak, Ma, Aboh, Kak Long, Kak Ngah, Kak Dah, Emy, Adik, Ayeh, Nor, Hafiz, Fakhrudin, and Izudin, who always gives a positive vibe so that I could finish this journey.

I would like to acknowledge my colleagues and officemates, Haizan, Nazira, Maria, and Bernard for their continuous support and creating a conducive work environment.

My special thanks to my sponsor, Universiti Malaysia Pahang and Higher of Malaysian Education for giving me the opportunity in pursuing my Ph.D. study.

Last but not least, a special appreciation for the special man who always will be my back and keeps supporting me spiritually throughout this journey.

Thank you very much.

ABSTRACT

The increasing amount of food waste (FW) is one of the most challenging problems around the world. The remarkable amount of FW produced is driven by various factors such as population growth, modernization, safety policy, culture, lifestyle, and human behavior. FW commonly will end up in the landfills and create more problems to the environment, ecosystem, human health, and economy. This organic waste is easy to decompose and emits greenhouse gases which will increase the global warming effect. Additionally, leachate from the landfill has the potential to contaminate nearby groundwater systems. It is important to divert FW from landfills and find a better option such as utilizing it to produce other value-added products. Depending on the FW composition, this waste has the potential to be used in fermentation technology and to be converted into ethanol as a primary product. Ethanol has a demand in different industries such as transportation fuel, cosmetic, pharmaceutical, and food. Additionally, waste from the fermentation process can be used as fertilizer in both liquid and solid form as it has a market value. In particular, solid waste stream can be burnt and converted into energy through combined heat and power (CHP) processes.

In this study, the main focus was to make a comparative assessment of the economic and environmental impact of FW fermentation on three value-added products: ethanol, liquid fertilizer, and bio-compost or energy. SuperPro Designer V9.0 simulation software was used to model the FW fermentation plant with commercial scale. Techno-economic analysis (TEA) and life cycle assessment (LCA) were used to determine the impact of this process.

A TEA study was conducted on five scenarios: (a) FW fermentation process with hydrolysis enzymes and 2-step distillation system, (b) FW fermentation process without

enzymes and 2-step distillation system, (c) FW fermentation process without enzymes and 1-step distillation system (d) FW fermentation process without enzymes and membrane distillation, and (e) combined heat process (CHP) integrated with FW fermentation process. Discounted cash flow analysis was used to estimate the minimum selling ethanol (MSE) price when a net present value (NPV) is equal to zero, and the internal rate of return (IRR) is 10%. Results from this analysis showed that the lowest MSE was $1.88 per gallon for the scenario (e) which reveals integrated with CHP to be the most economical process compared to the other scenarios in this study.

An LCA was conducted to compare the environmental impact of FW fermentation process to landfilling method. The LCA scope was to evaluate the global warming potential (GWP) from each process. As expected, FW fermentation had the lowest environmental impact in comparison to the landfilling method. From the results, fermentation with membrane separation process had the least GWP impact given by 164.1 kg $CO_{2\text{-eq}}$/1 Mg of FW compared to the other process depending upon assumptions.

Overall, this study has found the FW fermentation process to be a practical and sustainable way to manage FW rather than sending it to the landfills. This is an excellent opportunity to convert waste into cost-effective value-added products while minimizing the environmental burden.

CHAPTER 1. GENERAL INTRODUCTION

Food waste

In 2015, at least 1.3 billion tons of food was lost and wasted per year as reported by the Food and Agriculture Organization of the United Nations (FAO). This value is equivalent to the one-third of food produced for human consumption globally (FAO, 2013; Gustavsson, Cederberg, Sonesson, van Otterdijk, & Meybeck, 2011). Food waste (FW) is one of the most challenging problems around the world. The generation of FW is kept increasing every year. For example, in the United States, the FW has a significant increase from the year 1960 to 2015 as shown in Figure 1-1 (EPA, 2018a). The increasing amount of FW was expected associated with population and economic growth (Uçkun Kiran, Trzcinski, Ng, & Liu, 2014a).

FW sources was divided into three main groups; food loss, unavailable food wastage, and avoidable food wastage. Food losses are defined as lower in quality or quantity of food that typically happen at any stages in food value chains such as production, storage, processing or distribution. Unavoidable FW are known as spoiled and discarded food such as fruits peel while avoidable FW are edible food that suitable for human consumption but being uneaten leftover. Either waste or loss, both of these types are generally known as food waste (FW). Drivers of food wastage are by various factors such as food overproduction, inefficiency in the production process, quality issue, safety concern, and environmental change. All these causes have the potential to be reduced via engineering control except for behaviors by retailer and consumer (Gustavsson et al., 2011; Parfitt, Barthel, & Macnaughton, 2010).

The distribution of food loss and waste in developed and developing countries varies significantly (Buzby & Hayman, 2013; Gustavsson et al., 2011). Figure 1-2 shows that developed countries have more waste occur in end-user level, while for developing countries are most likely happen during production and handling stages (Lipinski et al., 2013).

About 76.1% of FW will be sent to the landfills as a common method disposal management system (EPA, 2018b). Hence, FW is found to be the most significant waste that will end up in the landfill as shown in Figure 1-3 (IPCC, 2006). FW is organic waste higher in moisture and consists of sugar and protein which easily ca be degraded and release air pollution. Large-scale landfill facilities could potentially cause air pollution and have a severe effect on human health (Alharbi, Basheer, Khattab, & Ali, 2018).

Furthermore, decomposition of FW in the landfill could release a higher amount of methane gas (CH_4) to the atmosphere and contributes to global warming impact (Heyer, Hupe, & Stegmann, 2013; Themelis & Ulloa, 2007). CH_4 has a 25 time greater adverse effect on the environment compared to carbon dioxide (CO_2) at trapping the heat over 100 years (EPA, 2010). The greenhouse gasses (GHG) emitted from the rotted FW at the landfill can be considered as the third largest GHG emitter in the world after China and the United States as illustrated in Figure 1-4 (Lipinski et al., 2015). Other than that, leachate from FW may have a significant potential to pollute groundwater near the site (Clarke, Anumol, Barlaz, & Snyder, 2015).

Apart from the environmental effect, FW also has an impact on economic. As mentioned, the generation of FW is proportionate with population growth. Due to expanding urbanization, space for landfill site becomes limited. Hence, the cost keeps increasing over the year because more land is required to open more landfill. Additionally, the tipping fees for disposal removal cost in the United States shows a significant increment from the year 1982 to 2015 as illustrated in Figure 1-5 (EPA, 2018b).

Although FW has disadvantages from an environmental perspective, it still contains relatively valuable resources that can utilize. Sugar is the highest component in FW, followed by proteins which in range of 35.5-69% and 3.9-21.9% respectively. Theoretically, this substrate are identified as an excellent source for microbial consumption and converted into various kind of marketable valuable products such as hydrogen, methanol, ethanol, organic acids, and bioplastic (Lin et al., 2013; Sun, Li, Qi, Gao, & Lin, 2014; Uçkun Kiran et al., 2014a; C. Zhang, Xiao, Peng, Su, & Tan, 2013)

Food waste conversion option for energy generation

There are two main pathways in FW to energy conversion; via thermochemical and biochemical process as shown in Figure 1-6. Incineration is a process that produces electricity from a steam turbine. FW will undergo a drying process before burning at temperature 850– 1100^{o}C to generate heat. Other than that, pyrolysis and gasification also knew as another thermal processes to use FW in producing energy. Bio-oil and syngas (combination of carbon dioxide (CO_2) and hydrogen) are the main product of this process. Pyrolysis required higher temperature (750-800^{o}C) without oxygen condition, while for gasification required temperature at 350^{o}C- 1800^{o}C with present of air, oxygen or steam (1-30 bar)(Grycová, Koutník, & Pryszcz, 2016). However, the thermochemical process is found to be energy intensive process due to higher moisture content (74-90%) and lower heating value which defined as the less amount of heat released by complete combustion of

FW, thus required the higher cost of operational (Pham, Kaushik, Parshetti, Mahmood, & Balasubramanian, 2015).

As for biochemical pathways, anaerobic digestion (AD) of FW is found to be a useful method and relatively mature that can produce biogas consisting of CH_4 and CO_2. This process occurred under controlled conditions and without oxygen present. Burning 1 m^3 of biogas can generate about 2.04 kWh of electricity (Murphy, McKeogh, & Kiely, 2004). However, this approach has a significant drawback such as higher retention time required, sensitive to environmental change (e.g., pH, temperature), intensive capital cost due to more substantial facility needs and negative impact on the environment (Chen, Cheng, & Creamer, 2008; Khalid, Arshad, Anjum, Mahmood, & Dawson, 2011; Pham et al., 2015; Xu, Li, Ge, Yang, & Li, 2018a).

Ethanol is can be the primary energy product from the fermentation process. This process has various pre-treatment methods because of the complex composition of FW such as chemical or physical process. Commonly, enzymatic hydrolysis to release sugars is used to facilitate the *Saccharomyces cerevisiae* fermentation process. Previous study has used different types of enzymes to enhance ethanol production using FW as a feedstock. For example, by adding enzymes α-amylase, amyloglucosidase and β-glucosidase in the fermentation broth, ethanol yield of 0.16 g / g dry FW will be obtained (Uncu & Cekmecelioglu, 2011). Similar to the result found by Kim et al., (2011), 0.2 g ethanol/ g FW yield obtained from this study using carbohydrase enzyme. Despite the fact pre-treatment in hydrolyzing could improve the ethanol yield, a higher cost of enzymes make this approach are not economical (Klein-Marcuschamer, Simmons, & Blanch, 2011a; Matsakas, Kekos, Loizidou, & Christakopoulos, 2014b; Pham et al., 2015).

Collectively, fermentation process for ethanol is widely used in the industry because this pathway is considered as a low capital cost and operational cost (Daystar et al., 2015; Foust, Aden, Dutta, & Phillips, 2009). However, the main issues in ethanol conversion through fermentation process are the enzymes cost is high. Therefore, the potential of ethanol production without enzymatic assistance provide the new challenge to reduce the production cost.

Ethanol

Energy is an essential requirement for human development. Adequate energy supply is a crucial tool to improve human life. Fuel for transportation is considered the second largest the energy demand and consumption worldwide. Previously, gasoline and diesel were the primary fuels used for transportation. However, when some issues occurred such as unsustainable resource, price inconsistency, the risk of energy security, and the impact of greenhouse gases, the focus on finding a new source has gained attention. Thus, the development of renewable fuel has led to worldwide interest in alternative energy sources, including biofuels.

To reduce the dependency toward fossil fuel, satisfy global demand, secure long-term sustainable fuel supplies, and increase awareness about the future environment give biofuels more attention for meeting human needs. Biofuels can be a form of liquid or gaseous fuel typically derived from the conversion of biomass materials. Ethanol and biodiesel are the most common types of biofuels available in the market.

Biofuels seem to be the most feasible alternative to fulfill the requirement in the transportation sector because of its characteristic. The significant benefits and impact of biofuels include: (a) economic: sustainability, fuel diversity, development of rural economy, job creation, increased investment in plant and equipment, agricultural growth, international competitiveness, and consistency in price, (b) environment: greenhouse gas emission reductions, reducing air pollution, biodegradability, higher combustion efficiency, and improved and water use, (c) energy security: domestic targets and distribution, supply reliability, availability, and renewability (Schnepf & Yacobucci, 2013).

In the United States, when the Renewable Fuel Standard 2 (RFS2) was introduced in 2007 by the Energy Independence and Security Act (EISA), biofuel production and consumption were being supported by this program. The RFS2 program requires biofuels to be blended into transportation fuel, and the volume requirement increases every year. By 2022, the mandate requires at least 36 billion gallons of renewable fuel to be produced and consumed (EPA, 2017). In this program, four categories of biofuels have been identified to fulfill the requirement. Table 1-1 shows the types of biofuel and the potential feedstock that are used in the commercial or in the research stage (AFDC, 2018). In RFS 2, volume mandate for cellulosic biofuels is expected to be increased every year to support the reductions in lifecycle GHG emissions.

Biofuels, either produced chemically or through the biological pathway, are considered the most viable alternative fuels. They can be used either blended with gasoline or directly in the vehicle. Government policy and mandate play an essential role to promote the use of biofuels in certain countries over the past decades. Ethanol (CH_3CH_2OH) is a type of alcohol generally derived from carbohydrate feedstock via biochemical conversion. It offers benefits for widely usage in diversification market. Therefore, ethanol is chosen to be discussed extensively, because it has more potential in the global market. It could be used for fuel, or other industry such as pharmaceutical, cosmetic, chemical and beverages industry (IEA, 2007). However, the focuses of this study are more to ethanol for fuel industry.

Ethanol blended with gasoline is commonly used for transportation fuel. Two standard blended rates accepted worldwide are E5 (5% ethanol, 95% gasoline) and E10 (10% ethanol, 90% gasoline), and they show good compatibility with existing engines. Besides that, a higher ethanol concentration rate such as E85 is only suitable for a flex-fuel vehicle with a modification of the engine. Ethanol is more favorable than other alternative fuels because of its attribute as a less toxic and more efficient fuel. It has a higher octane rating compared to gasoline, faster cooling ability, broader flammability limits, higher flame speeds, and higher heats of vaporization (Balat & Balat, 2009). Thus, theoretically, it can improve the knock resistance and increase engine efficiency over the gasoline (Larsen, Johansen, & Schramm, 2009). It is considered as a great option to substitute the methyl tert-butyl ether (MTBE) which is generally more harmful to humans than ethanol.

Starch and sugar crops have been dominant in the United States and Brazil‘s ethanol fuel industry which account for at least 85% of the global market (Bertrand, Vandenberghe, Soccol, Sigoillot, & Faulds, 2016). For example, corn ethanol conversion both by dry or wet mill processing is widely used in the United States and mostly concentrated in the Midwest area. In Brazil, sugarcane is the primary feedstock in ethanol industry because of weather condition is favorable to sugarcane plantation. Moreover, it has more energy yield than corn. According to (M. Wang, Han, Dunn, Cai, & Elgowainy, 2012) ethanol derived from sugarcane has the potential to reduce GHG emission by 40-62% compared to gasoline.

Food crops as a feedstock are known as the first generation of biofuels. Higher energy content is the main reason this biomass was chosen and extensively used in commercial biofuel production. However, negative impact from issues such as food vs. fuel, food security, increasing food price (Chakravorty, Hubert, & Ural Marchand, 2018; To & Grafton, 2015; Z. Zhang, Lohr, Escalante, & Wetzstein, 2010), and deforestation (Havlík et al., 2011; Solomon & Barnet, 2017) have led to the emergence of a new generation of biofuels to fulfill the energy demand while passing the previous problem.

Non-food feedstock for biofuels production is known as second generation (2G) which is found to be more economically feasible, environmentally friendly, and more sustainable (Saini, Saini, & Tewari, 2015). The potential feedstock for 2G biofuels as listed in Table 1-1. However, most of the cellulosic feedstock required essential pre-treatment to breakdown hemicellulose and cellulose into fermentable sugar. Thus it can be directly utilized by the microorganism. Chemical pretreatment such as enzymes, dilute acid and ionic liquid are commonly used in the process. Even though this method could have significantly increased product formation, however, it is cost intensive (Zheng, Pan, & Zhang, 2009). Since pre-treatment has the potential to reduce the operational profit hence, there is a still challenge to sustain the commercially viable for 2G biofuel process.

The Environmental Protection Agency (EPA) has approved fuel pathways under the RFS2 program which increases the mandated usage volume and extends the time frame over the volumes ramp until 2022. The biofuels qualifying under RFS2 must achieve certain minimum thresholds of lifecycle GHG emission performance. EPA has categorized that cellulosic biofuels should be produced and meet 60% lifecycle GHG reduction. According to the mandate, cellulosic ethanol is the second highest required volume compared to the others in the future. There are various types of potential feedstock for cellulosic ethanol which getting more attention by the researcher as shown in Table 1-1. However, ethanol conversion from food waste seems to be interesting to investigate the feasibility. This unwanted food would become economically attractive because of no cost for feedstock. The previous study has found the feedstock cost is the primary driver for higher product value (Mustapha, Bolkesjø, Martinsen, & Trømborg, 2017; Piccolo & Bezzo, 2009; Swanson, Platon, Satrio, & Brown, 2010). Therefore, the direction of this study is to address the questions of how food waste can be utilized and contribute to the economic and environmental impact. Figure 1-7 shows the general process of ethanol conversion process via fermentation, followed by separation and purification process. The research goal is to evaluate the impact of utilizing food waste using techno-economic analysis (TEA), and life-cycle Analysis (LCA) approaches in producing ethanol as the main product. Besides that, liquid fertilizer, bio-compost, and electric power are anticipated to have a significant factor to determine the economic impact of the overall process.

Fermentation

Over a decade, the global ethanol production was exploited via the fermentation process by *Saccharomyces cerevisiae* and remains as prime species. Either using the starchy or sugar feedstock, the metabolic pathway will be the same. The only difference is the starch feedstock required pretreatment such as enzymatic hydrolysis to break down the glucose polymer to the simple molecule. The main metabolic pathway involved is glycolysis. Metabolizing of one-mole glucose (C6) will produce two molecules of pyruvate acid, CO_2, and ethanol under an anaerobic condition as illustrated in Figure 1-8. Besides that, two units of ATPs generated in this process will be used to provide energy for the biosynthesis of yeast cells.

The overall chemistry process for the fermentation process is to convert glucose sugar ($C_6H_{12}O_6$) to ethyl alcohol (CH_3CH_2OH) and CO_2. Theoretically, 100g of glucose will convert to 51g ethanol and 49g carbon dioxide.

Separation process

Commonly, the distillation process is used for ethanol recovery from the fermentation broth. However, lower ethanol concentration (less than five wt%) will require higher energy consumption (Madson & Lococo, 2000). At least, 40% of the total energy consumption in ethanol production is coming from the distillation process (Endre Nagy & Boldyryev, 2013).

Typically, a multi-column distillation system is used to achieve higher purity of ethanol product. The 2-step distillation system with ethanol-water azeotropic and recovery column is sufficient for producing fuel-grade ethanol (Kwiatkowski, McAloon, Taylor, & Johnston, 2006). The first column is known as a beer column which will yield about 55% (v/v) ethanol in the distillate. The second column incorporated with rectifying and stripping system will produce 95-96% of ethanol. The distillate from the second column will purify up to 99% using a molecular sieve (Brown & Brown, 2014a; Kwiatkowski et al., 2006). Hence, in this study, two column distillation has been used to increase ethanol purity. The process flow diagram for the distillation process as illustrated in Figure 1-9.

Distillation is the only method that applied in the industry. Even though distillation is one of the most effective liquid-liquid separation techniques, it received some critical disadvantage, higher cost, energy-intensive process and limitations on separation of volatile organic compounds. Hence, there are challenges to determine another alternative method in the separation process that more feasible and economically viable. Membrane separation either by using hydrophobic (ethanol permeates) or hydrophilic membranes (water permeates) operations are expected to be the most energy-saving method for the production of ethanol. Thus, by reducing the cost, the energy consumption and net carbon footprint of this process can significantly influence the sustainability and economic feasibility of ethanol from food waste. In the next chapter, the comparative techno-economic analysis on ethanol recovery process will be discussed further.

The integrated combined heat process

Integrated with combined heat process (CHP) is a system that could produce heat and electricity in-site by burning solid waste from the process. The chemical energy will be turned into heat energy that can be used to run the steam turbine. By using the Rankine cycle principle, the steam turbine can produce electricity which will distribute back to the process. The backpressure steam turbine is commonly used in the industrial plant because of the low capital cost, simple configuration and high efficiency (DOE, 2016). The steam exhausts from the system will be recovered and use directly to a process and steam distribution. This technology has suggested by the previous study to be implemented because it has potential to increase the plant profitability (Daiainova, Dotzauer, Thorin, & Yan, 2012; Dias, Lima, & Mariano, 2018; Eriksson & Kjellstrom, 2010; Raj, Iniyan, & Goic, 2011). The simplified integrated CHP with FW fermentation process is presented in Figure 1-10. Therefore, the economic study will be carried on in the next chapter to evaluate the impact of this combined technology and expected to have a significant effect on product value.

In this study, to determine the feasibility of new technology for commercialization, economic and environmental perspective should be evaluated. Both of this assessment will provide some information and understanding to the future investor. Estimated the product value can assess the economic impact. The greenhouse gasses emission release from the process, mainly focus on global warming potential (GWP) are expected to be determined and compared.

Understanding the economy and environmental impacts

In this work, the TEA and LCA approaches were employed to see the potential of energy conversion from food waste in the economic and environmental perspective. This evaluation could provide a piece of information about the sustainability of this process. The fermentation without hydrolysis enzymes was carried out to find the feasibility of utilizing FW to produce value-added products in commercial scale. The process was modeled using the SuperPro Designer V9.0, and the product conversion will be validated with the lab-scale experiment results. The techno-economic analysis is a tool that will be employed in this study to determine the cost impact and product value. GHG emission analysis also considered as the main aspect of assessing the environmental effects for particular scenarios. Furthermore, the commercial plant of FW fermentation has never been investigating extensively and recommended by Karmee (2016). Hence, it may provide a new research area with broader impacts.

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Figures

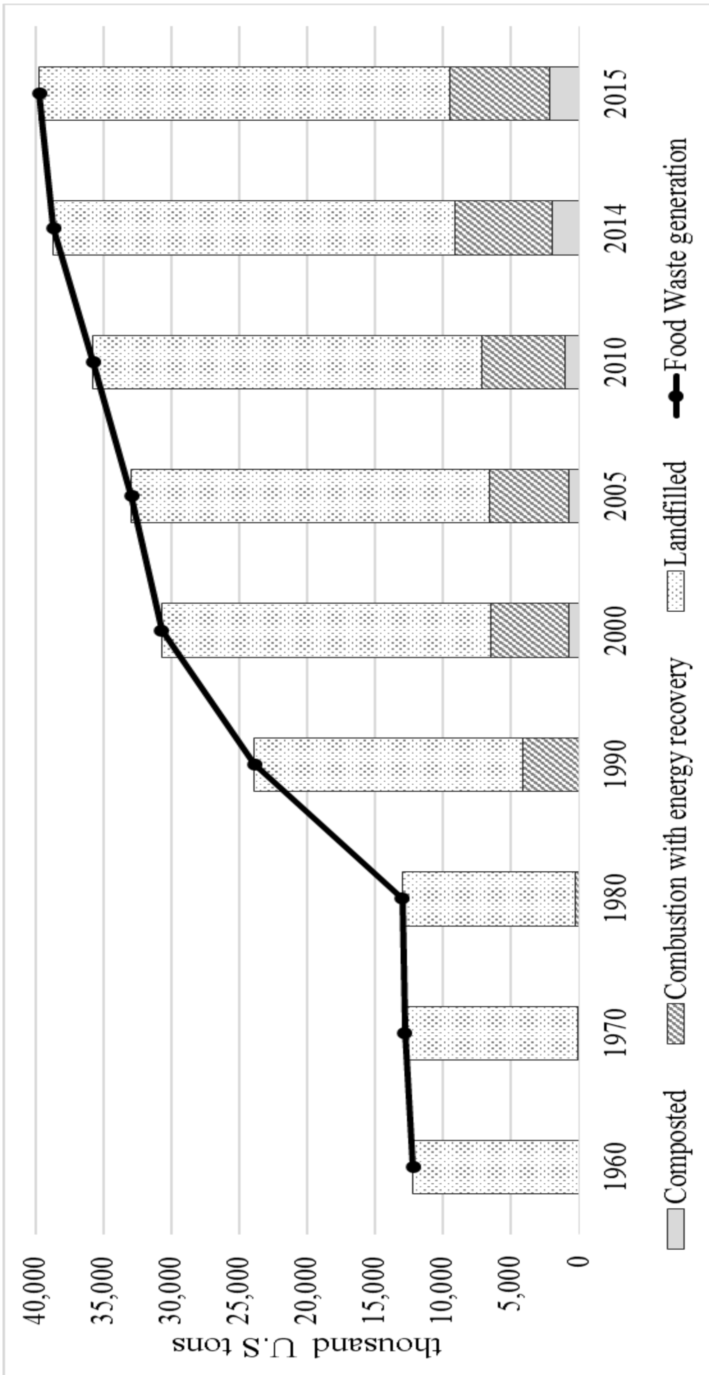

Figure 1-1 Food waste in municipal solid waste by weight from the year 1960-2015(EPA, 2018a).

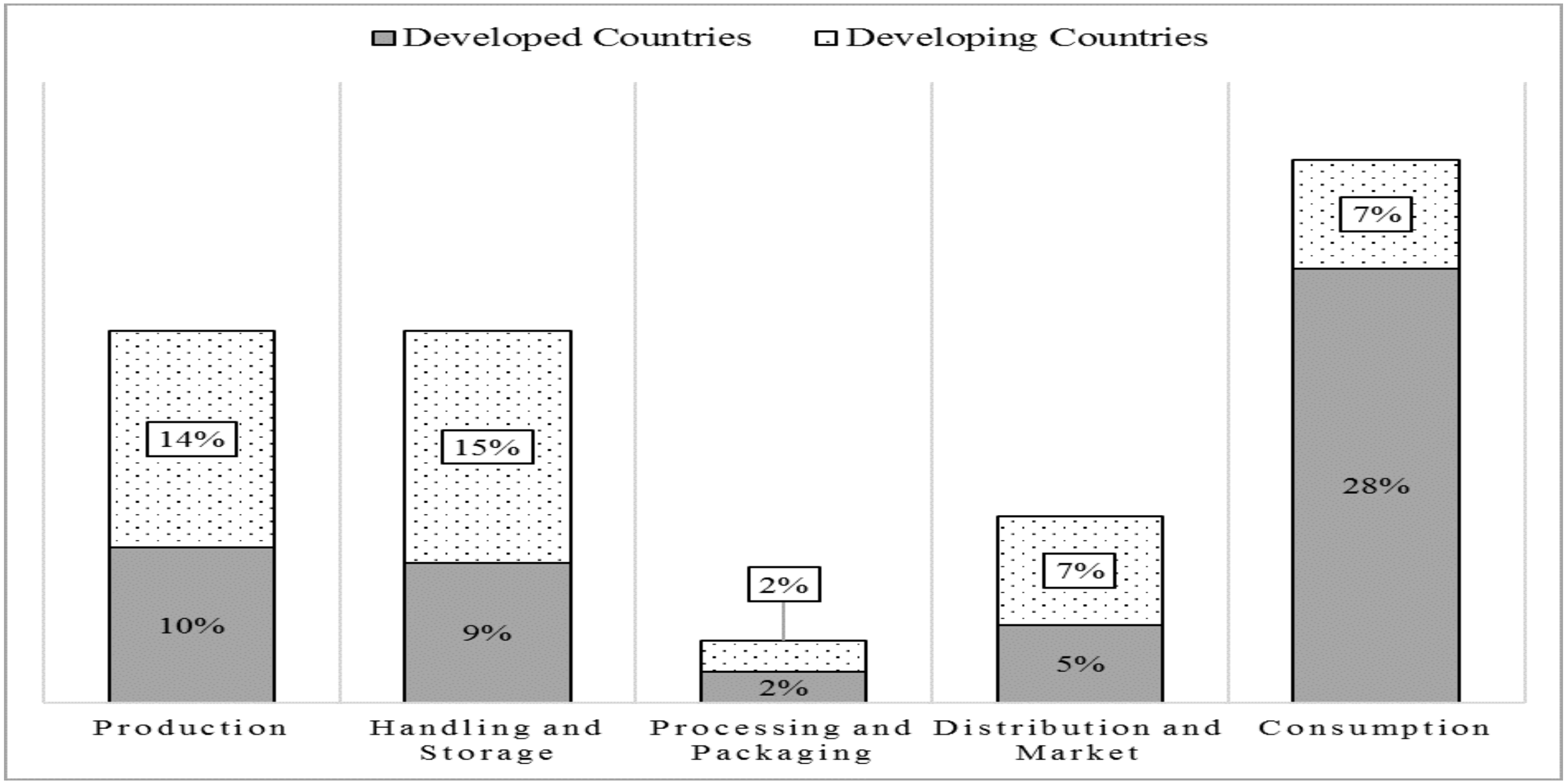

Figure 1-2 Total food waste and loss by stage (Lipinski et al., 2013).

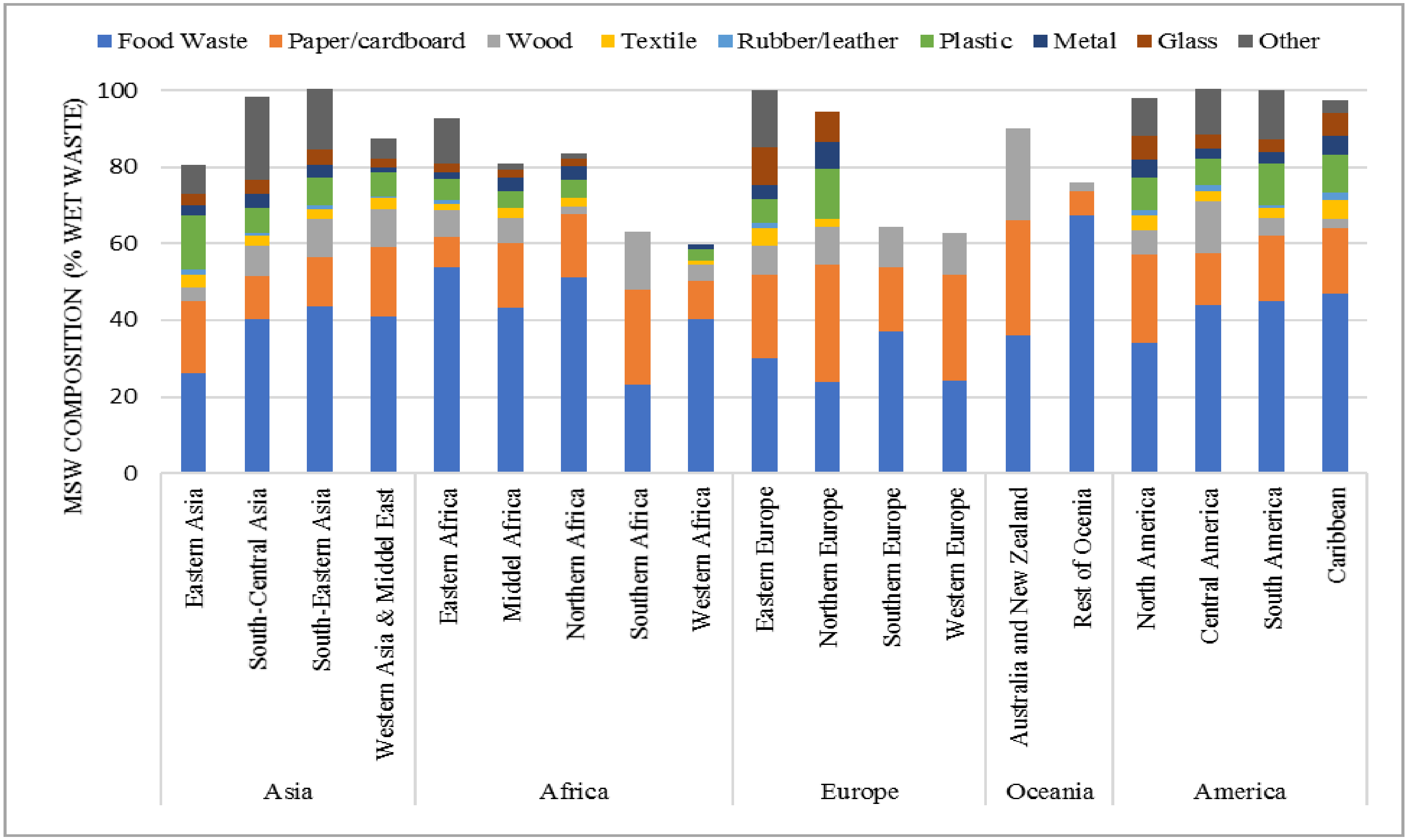

Figure 1-3 Percentage of municipal solid waste compositions by regions and countries (IPCC, 2006).

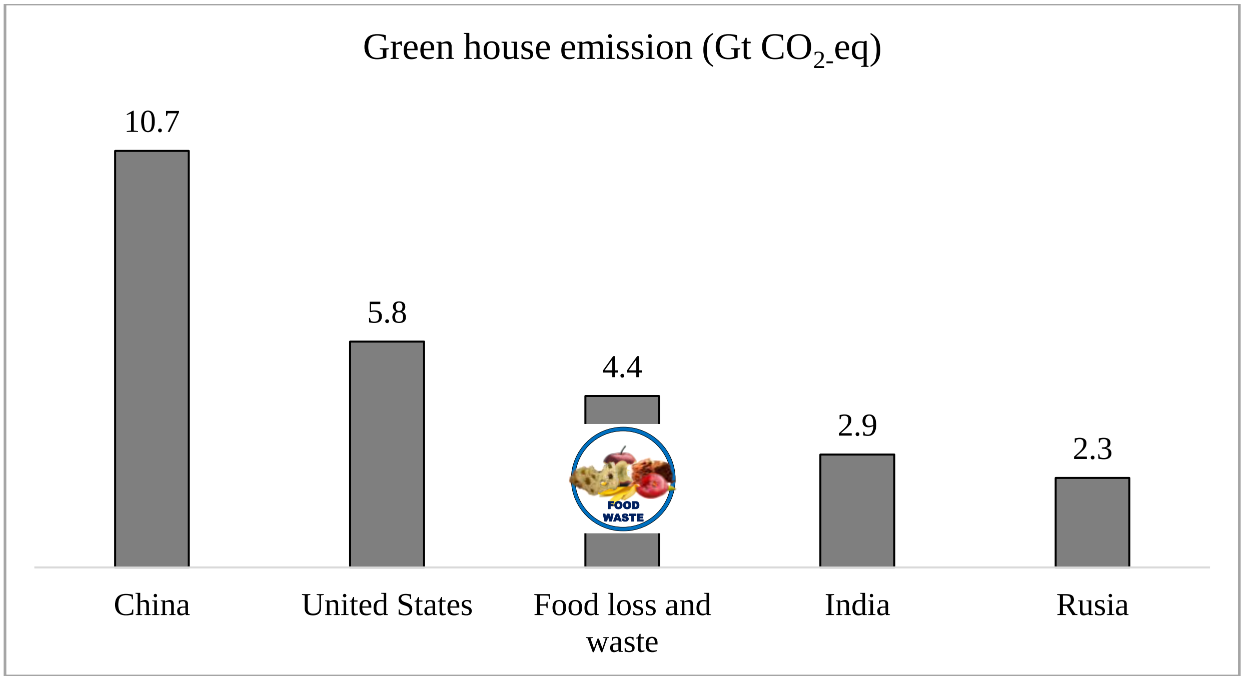

Figure 1-4 Greenhouse gas emission (Lipinski et al., 2015).

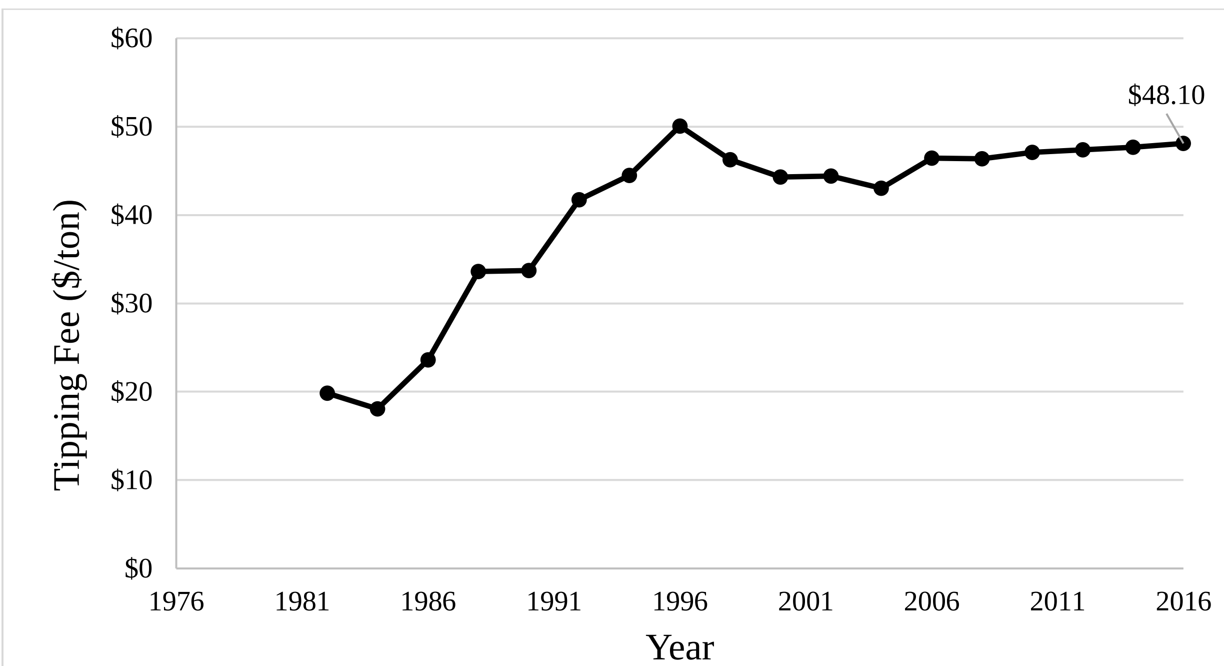

Figure 1-5 National landfill tipping fees ($2015 per ton) (EPA, 2018b).

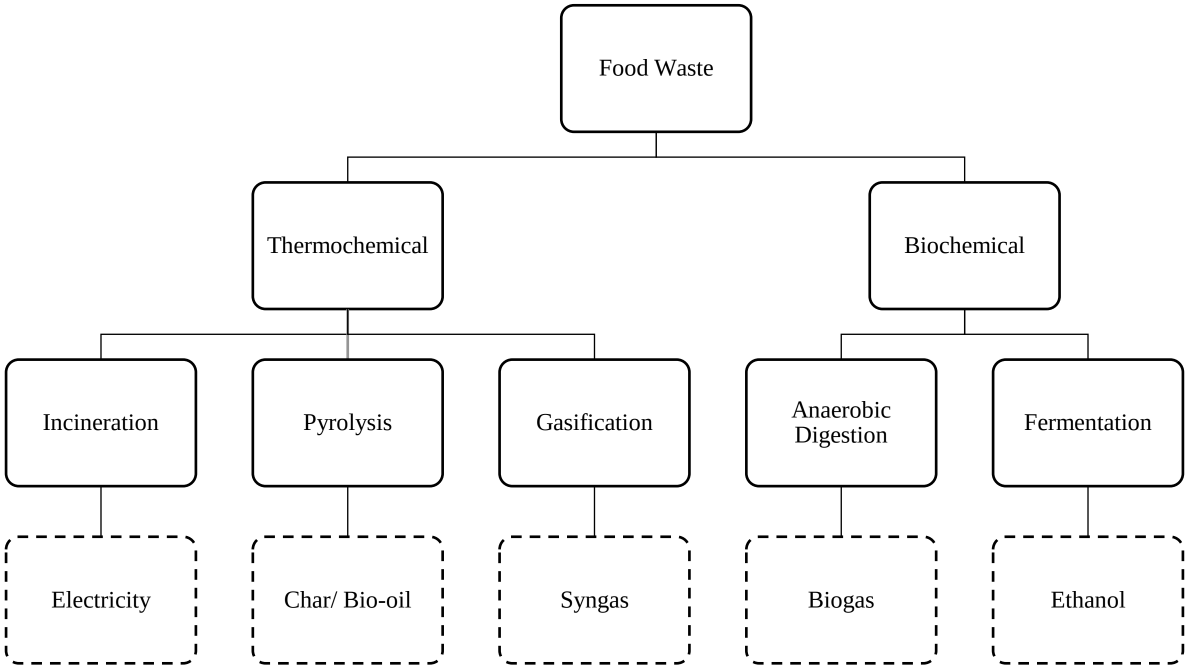

Figure 1-6 Conversion process of food waste to other energy.

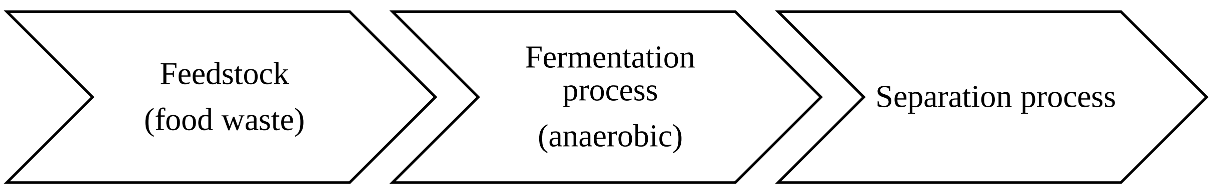

Figure 1-7 Process flow for the ethanol production process.

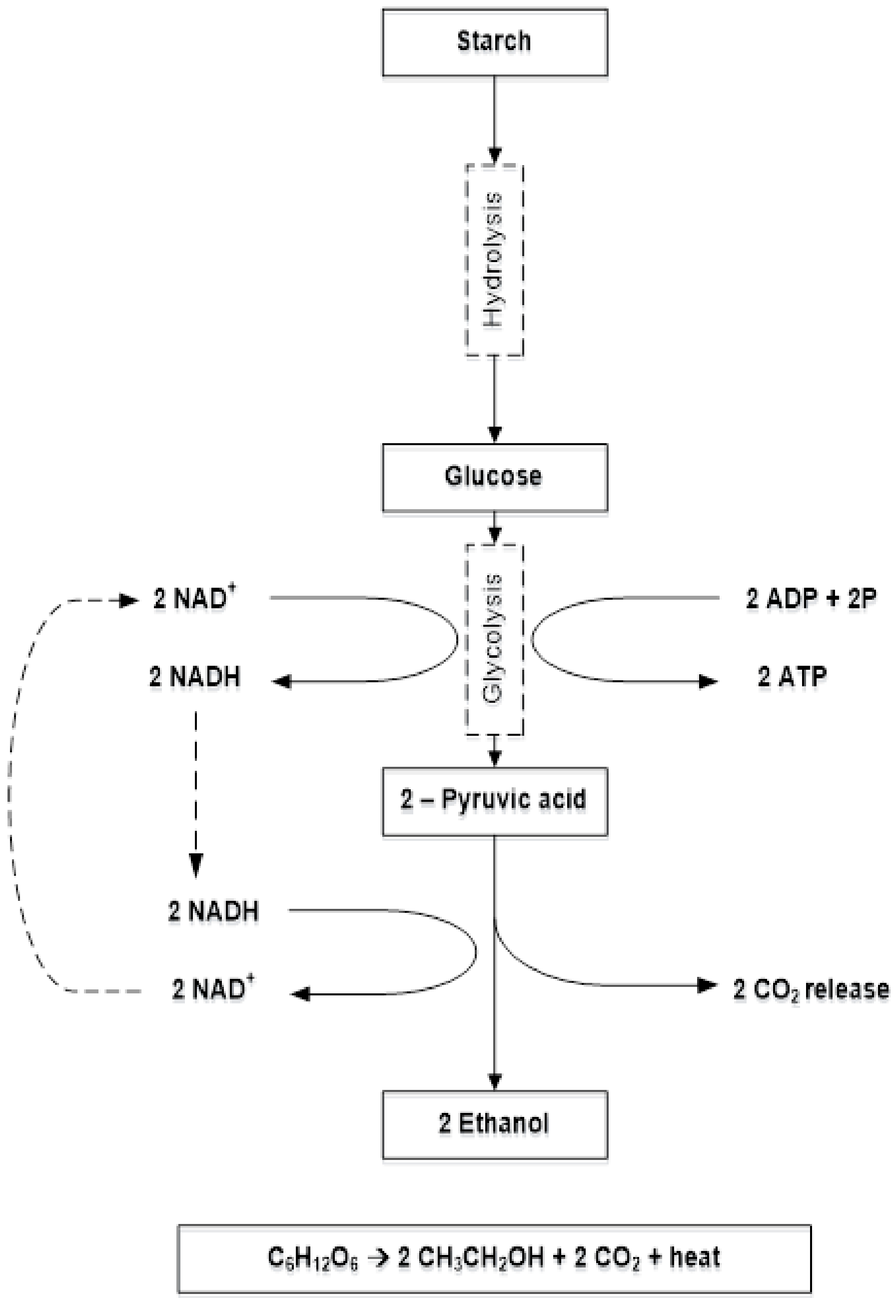

Figure 1-8 Metabolic pathway of ethanol fermentation.

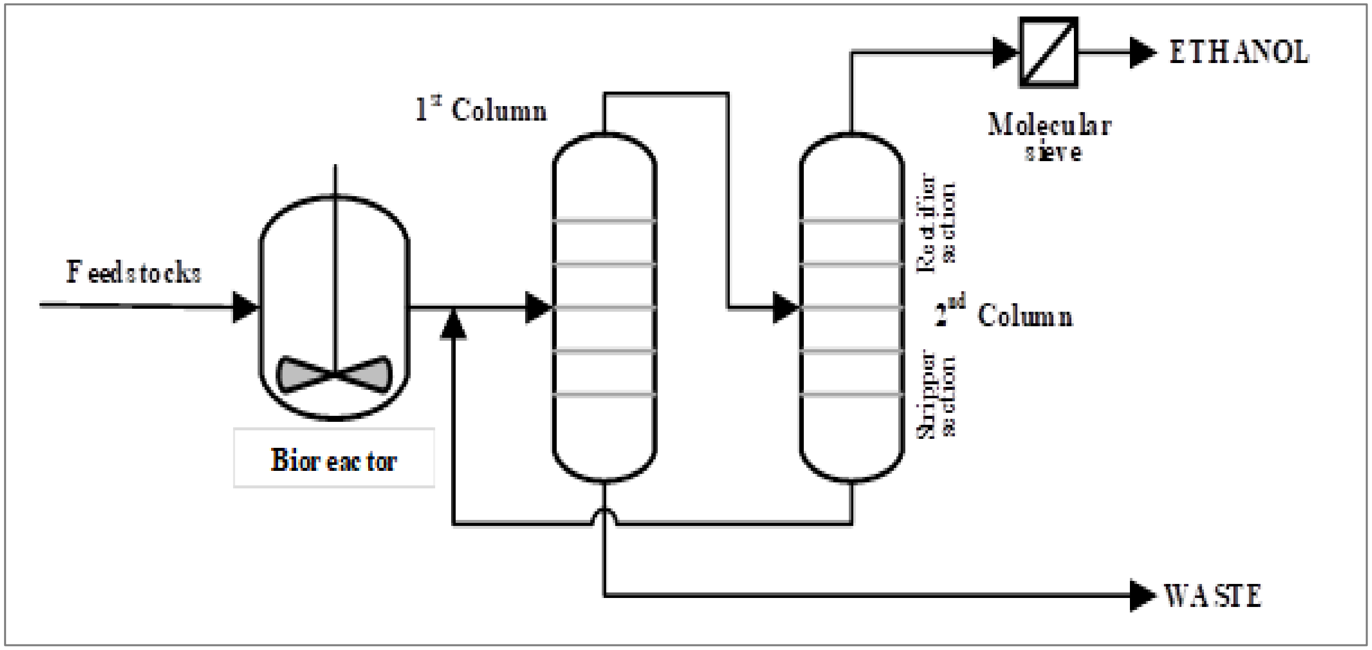

Figure 1-9 Process Flow diagram for ethanol separation using distillation column.

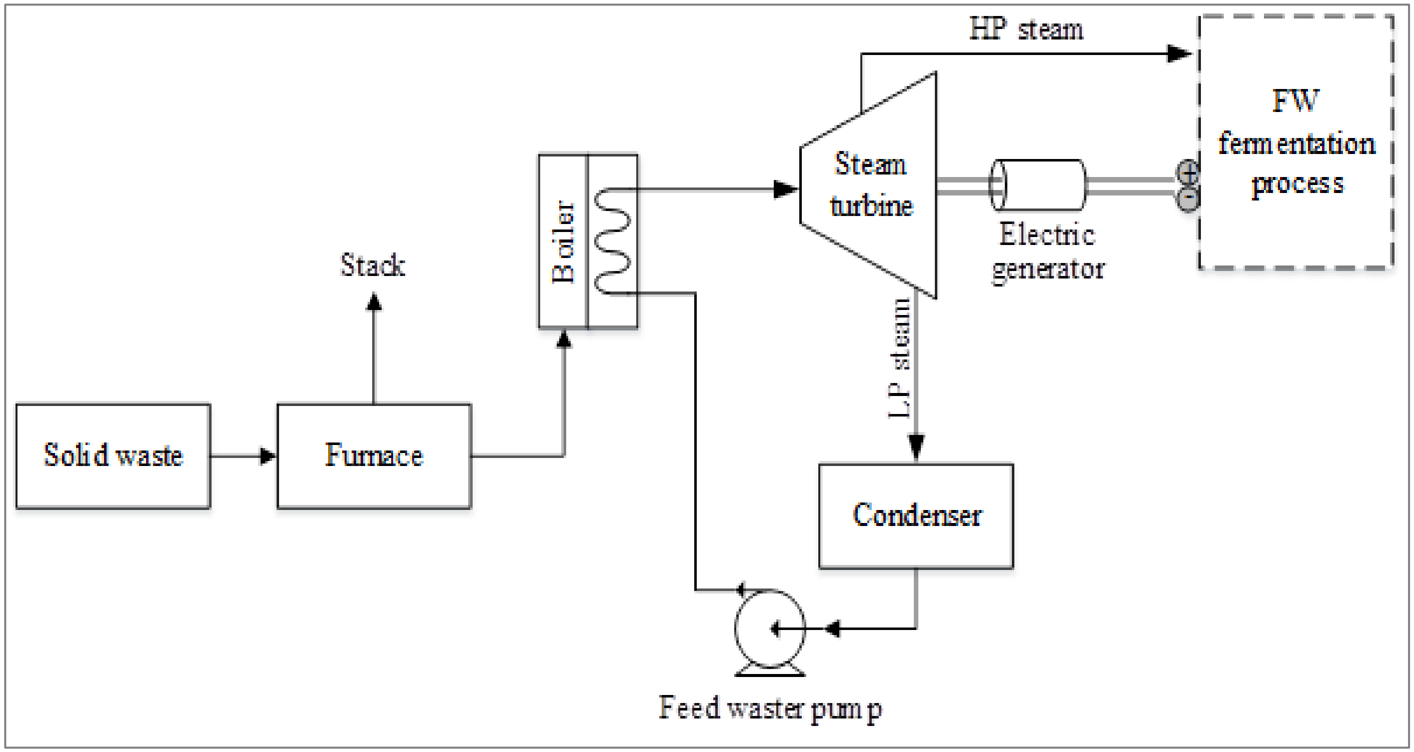

Figure 1-10 Combined heat process schematic diagram.

Tables

Table 1-1 Biofuel categories as stated in Renewable Fuel Standard (RFS) (AFDC, 2018).

Categories	Potential Feedstock
Cellulosic biofuel	Cellulosic, hemicellulose or lignin from renewable biomass such as dedicated crops (i.e., switchgrass and Miscanthus), crop residues (i.e., corn stover and sugar bagasse), planted trees and residues, algae, yard, and food waste.
Bio-based diesel	Distillate replacements produced from vegetable oil, animal fats, waste grease, animal waste, and byproduct.
Another advanced biofuel	Any which qualifies for cellulosic category + sugar-cane or non-corn starches, butanol, biogas
Renewable biofuel	Any which qualifies for cellulosic or advanced categories + cornstarch

CHAPTER 2. ORGANIZATION, OBJECTIVES, AND HYPOTHESIS

Organization

This dissertation is divided into three main area: (I) experimental study for FW fermentation without enzymes to produce ethanol, (II) techno-economic analysis (TEA) for commercial scale of FW fermentation process in producing value-added products with five main scenarios and (III) comprehensive comparison on the environmental impact of FW fermentation processes to landfilling method by using lifecycle assessment (LCA). The overall research study flow is presented in Figure 2-1.

The preliminary study is a lab-scale experiment conducted to determine a parameter that impacts the ethanol production without hydrolysis enzymes. The highest ethanol yield and fermentation conditions will be used in the commercial scale plant simulation. Chapter 3 will present the finding from this experiment.

A TEA is a study to estimate minimum selling ethanol (MSE) price by using discounted cash flow analysis. Ethanol is considered as a primary product and waste stream from the process will be sold as a co-product based on market value. The five scenarios will be divided into three main sub-study and will be reported in chapter 4, 5 and 6.

An LCA study is a study to compare the environmental burden from FW fermentation process plant to landfilling method. The main focus is to evaluate the global warming potential (GWP) effect in kg CO_2-eq/ 1 Mg of FW Results from this analysis will be reported in chapter 7.

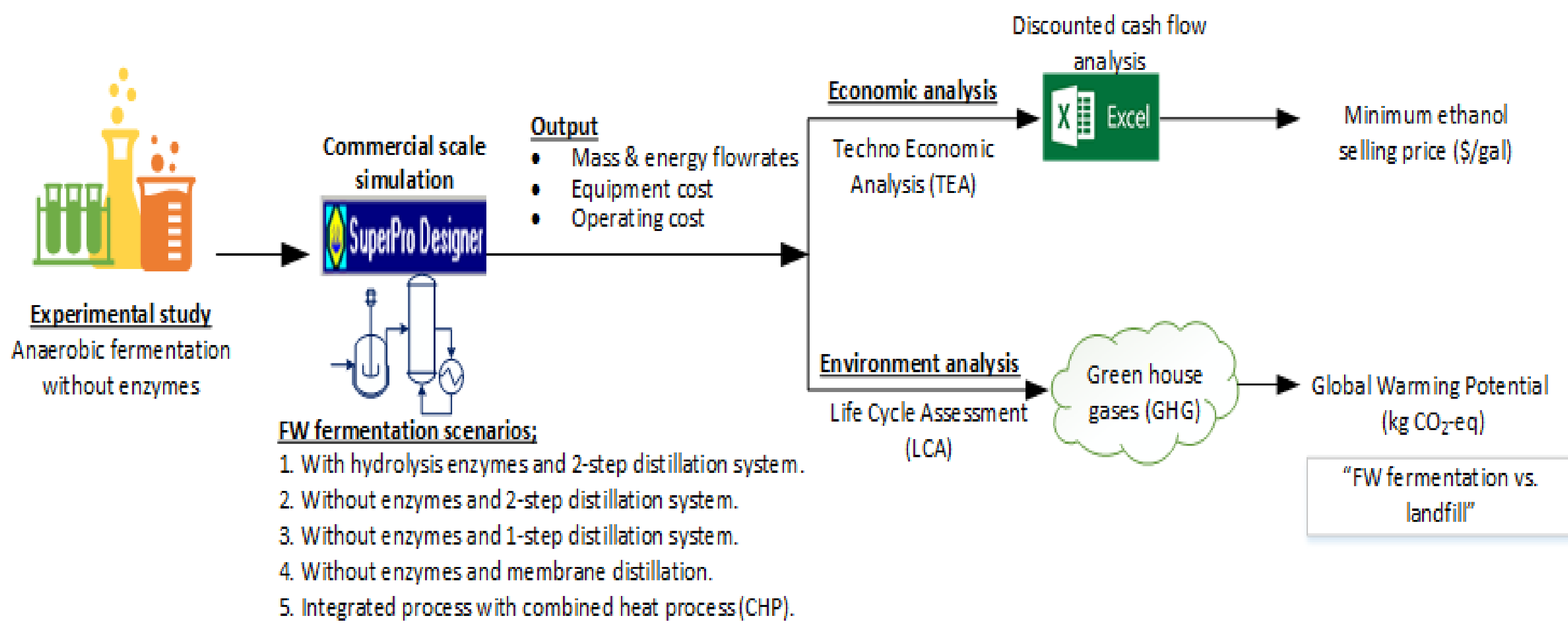

Figure 2-1 Design of study.

Objectives and hypothesis

The performance of value-added products conversion from food waste (FW) will be investigated in this study. The main focus was to make a comparative assessment of economic feasibility and environmental impact of commercial-scale FW fermentation process plant. Hence, the specific objectives and hypothesis of this research study are listed as follows:

Study 1 : Determination of significant parameters for ethanol production from food waste

Objective : To determine the significant parameters of ethanol production from FW without any enzymatic assistance.

(Ho) : All main parameters and interaction do not significantly affect the ethanol yield.

Study 2 : Techno-economic evaluation of food waste fermentation to value-added products

Objective : To evaluate the TEA of commercial-scale FW fermentation to value-added products.

No hypothesis was formally tested due to computer modeling related

Study 3 : Economic assessment of ethanol recovery using membrane distillation in food waste fermentation

Objective : To identify the economic potential of ethanol recovery using membrane distillation in FW fermentation.

No hypothesis was formally tested due to computer modeling related.

Study 4 : Economic evaluation of combined heat process (CHP) integrated with food waste based ethanol production plant

Objective : To determine the economic performance of ethanol production with combined heat power process in commercial scale FW fermentation process.

No hypothesis was formally tested due to computer modeling related

Study 5 : Comparison of global warming potential impact of food waste fermentation plant with landfills disposal method

Objective : To compare the global warming potential impact on utilization of FW fermentation process with landfills disposal method.

No hypothesis was formally tested due to computer modeling related

CHAPTER 3. DETERMINATION OF SIGNIFICANT PARAMETERS FOR ETHANOL PRODUCTION FROM FOOD WASTE

Modified from paper will be submitted to the *Waste Management* journal.

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Abstract

Food waste (FW) is kept on increasing every year due to various factors such as exponential population growth, modernization, safety policy, and lifestyle. The remarkable amount of FW is a severe global issues. Commonly, this waste will end up in the landfills as a disposal option. The decomposition of FW could occur naturally and will be emitted greenhouse gasses which create more problems for the environment, ecosystem, human health, and economy. The composition of this waste is suitable to be used to produce ethanol through anaerobic fermentation. Therefore, in this study, the significant parameter in FW fermentation without hydrolysis enzymes will be determined. The experiments were conducted under open anaerobic fermentation conditions with 18 combinations of independent variables, including pH (3.0, 4.0, and 5.0), temperature (25°C, 30°C, and 40°C) and agitation rate (100rpm and 150rpm). Results from this experiment found that the maximum ethanol yield is 2.2 % (w/w) wet basis with a pH value of 5.0, a temperature of 30°C, and 150 rpm. From the statistical analysis, all the main effects and interaction were significantly affecting ethanol production. This finding suggests with these conditions, FW

has the potential to be utilized as main substrates without enzymes in producing ethanol. Therefore, it could reduce the production cost in commercialization.

Introduction

Energy is one of the primary drivers for the development of human civilization. Exponential population growth causes the energy demand to increase every year. The U.S. Energy Information Administration has reported that at least 29% of energy was used for transportation in the United States in 2017 (EIA, 2018), and crude oil and its derivatives remain as a primary transportation fuel. Issues such as price inconsistency, shortage supply, and environmental problems lead the world to seek new sources of clean and sustainable energy. Ethanol was found to be a viable alternative fuel because it is more environmental friendly than gasoline and helps to improve energy security. Several studies have found that ethanol can be produced from substrates that rich with sugar through a biological technologies process. As listed in the biofuel categories as stated in Renewable Fuel Standard (RFS), energy crops, biomass, and food waste are the potential feedstock in producing ethanol (AFDC, 2018).

FW is identified as the most significant waste stream by weight in landfills. It has higher in moisture content, bulk density and rich in nutrients. This organic waste is easy to decompose naturally by microorganisms. Commonly, FW consists of food either left uneaten or discarded during processing. As reported in the National Resources Defenses Council (NRDC), the United States generates at least 40% of FW yearly, which equivalent to $165 billion. Most food waste will end up in landfills as a disposal option and emit up to 16% of the methane emission in the U.S (Gunders, 2012).

Several studies have shown that carbohydrate is the major component of FW. As reported, the percentages of sugar and starch have been found as 55% and 25% (wet basis) respectively. (Cekmecelioglu & Uncu, 2013; Hafid, Rahman, Md Shah, & Baharudin, 2015; Ohkouchi & Inoue, 2007; Vavouraki, Angelis, & Kornaros, 2013; Q. Wang et al., 2008). Commonly, microorganisms such as yeast can convert carbohydrate into ethanol through anaerobic fermentation. Therefore it is interesting to utilize the FW in producing ethanol because it consists of higher sugar content. From this study, it could support the idea of FW as a potential feedstock for producing ethanol.

Previous studies have revealed the potential of food waste as a feedstock to produce ethanol. Most of the research studies are using enzymes such as α-amylase, amyloglucosidase and protease (Hong & Yoon, 2011), carbohydrase, glucoamylase and cellulase (Kim et al., 2011), or Termamyl 120L, Spirizyme Plus and Viscozyme (Li et al., 2011) to enhance ethanol production. However, adding enzymes in the process required another process to activate the activity of the enzyme (Khawla et al., 2014). Therefore according to the previous study, the enzymes usage are found to be the second largest cost and not economically feasible because of more unit operation are required. Additionally, the high price of enzymes will lower plant profitability. (Klein-Marcuschamer et al., 2012; Klein-Marcuschamer et al., 2011). Despite this limitation, there has yet been no extensive study on using food waste for ethanol production without additional enzymes in the fermentation process.

Besides enzymes, there is another factor such as pH, temperature, types of microorganism and substrate could have a significant impact on increasing the fermentation efficiency. Thus, the aim of this study is to determine the significant parameters for ethanol production by FW fermentation without enzymatic assistance. Anaerobic fermentation by *Saccharomyces cerevisiae* will be used in this study. The hypothesis of this study is all main parameters and interaction do not significantly affect the ethanol yield will be tested.

Material and methods

Substrate and fermentation conditions

Post-consumer food waste was obtained from ISU Dining at Iowa State University and ground using a blender (KitchenAid KFP1133CU food processor). The samples were kept in the chiller with the temperature maintained at 4^{o}C to prevent other reactions occurring during storage. Dry *Saccharomyces cerevisiae* (RED STAR Quick® Rise ™ Yeast ™) was used to induce ethanol fermentation. Bench-scale fermentation experiments were carried out in an erlenmeyer flask with a rubber stopper and incubated in an incubator shaker (Excella E24 Incubator Shaker series, New Brunswick Scientific) at speeds of 100 and 150 rpm. The dry yeast was diluted with deionized water (10 g/L) and added to the fermentation broth without cultivation (Uncu & Cekmecelioglu, 2011). In this study, pH ranges of 3.0, 4.0, and 5.0 were adjusted using 3M NaOH and H_2SO_4. The open anaerobic fermentation was performed at temperature condition 25^{o}C, 30^{o}C, and 40^{o}C for 96 hours, and at the end of the fermentation process, ethanol concentration was analyzed using an HPLC.

Analytical analysis

Samples obtained from fermentation and centrifuged at 2000 rpm for 10 minutes. The supernatant was filtered using PTFE filters with pore size 0.45 µm. The sample was injected into an Aminex HPX-87H, 300 mm x 7.8 mm column (BioRad, Hercules, USA). The column temperature was maintained at 50°C. 0.01N Sulfuric acid was used as a mobile phase with a flow rate of 0.6 ml/min at a pressure of 493 psi and an injection volume of 20 µL. Ethanol concentration was analyzed using an HPLC (Varian 356-LC) with a refractive index detector.

Experiment design and data analysis

The experiment design can be seen from Table 3-1, and the experiment was carried out in triplicate. The values obtained are the mean of ethanol yield (% w/w) of a combination of independent variables.

The effect test was generated using a JMP Pro 12.0 (SAS Corporation, USA). The statistical analysis worked on the null hypothesis (P-value <0.05) by first stating that each parameter and associated interaction had no significant effect on ethanol yield. An HSD Tukey's test has been applied to determine the differences between group means and to indicate the highest value of ethanol yield with statistical significance at a 0.05 probability level.

Results and discussions

The substrate was analyzed using HPLC only to measure the simple sugar compositions before the fermentation process. From the result, monosaccharides and disaccharides were found to be the main component in the substrate with concentration value 15.2 g/L. The moisture content of food waste, (78.71%) was determined using an oven drying method at 135°C for 2 hours (AOAC, 2005; method 930.15). From the theoretical, yeast can convert sugar (glucose, fructose, and sucrose) into ethanol and cellular energy via anaerobic fermentation. Although starch was present in the feedstock, however, yeast could not ferment it immediately because of lack of enzyme amylase.

Ethanol yield was measured using HPLC after the fermentation. The average ethanol yield for each condition can be seen in Figure 3-1. On average, it clearly showed the maximum ethanol yield obtained from the experiments was 2.2% (w/w) wet basis. Further analysis from post hoc comparison revealed that mean for ethanol yield at pH of 5.0, a temperature between 30^{o}C, and a 150 rpm agitation rate was significantly higher than other process conditions. A similar finding by Narendranath and Power (2005), the optimum pH value to enhance the fermentation yield should be in between 5.0 and 5.5. As a comparison, the ethanol yield from this study is considerably higher than studies by Suwannarat and Ritchie (2015) for similar feedstock and conditions because most of the nutrient is not degraded by the sterilization process before the fermentation process.

According to a study by Lin et al., (2012), even without enzymes assistance, the fermentation yield can be enhanced by controlling other parameters and conditions. Thus, finding from this study could be a potential method to be applied in commercial scale because it could minimize the operational cost.

To identify the most critical parameter factor in this fermentation study, a fit model was used to formulate a regression equation. The linear model equation for the ethanol production Y as a function of ethanol yield (%) and variables X_1 as pH, X_2 as temperature (degree C) and X_3 as agitation rate (rpm) is found to be:

$$Y = 0.273X1 + 0.025X2 + 0.014X3 + 0.03X1X3 - 2.53$$

Equation 3-1

Equation 3-1 shows that a one-unit increase in pH yields a 2.2 % (w/w) wet basis increase in predicted ethanol yield holding temperature and agitation rate constant. It shows that pH is the most significant parameter that could impact ethanol yield. However, there is a limitation for pH value because of the too acidic environment; yeast cell activity will be inhibited.

Statistical analysis was performed to determine the effect of each parameter and its interaction concerning ethanol production. Fermentation experiments were designed with random values for each independent variable, e.g., pH, temperature (^oC), and agitation speed (rpm). Each condition of the experiment was performed in triplicate, so the means of ethanol production (g/L) were measured (n=3). Table 3-3 shows the results of independent variable effect tests and associated p-values, indicating that all main effects and interactions were significant ($P < 0.05$), so failure to reject the null hypothesis for a parameter will have no significant effect on the production of ethanol concentration using food waste at a 95% confidence interval.

Conclusions

This study focused on ethanol production from FW without hydrolysis enzymes. In this study, the optimal pH, temperature, and rpm are found to be 5.0, 30^oC, and 150 rpm, respectively with higher ethanol yield of 2.2% (w/w) wet basis. The linear model obtained from statistical analysis shows that pH is the most significant parameter for ethanol production. Results from the study showed that the main effects and interaction were statically significant in ethanol production from FW fermentation without enzymes.

From the previous literature, enzymes cost is one of the parameters that will reduce profitability. Thus, this finding has shown promising conditions to utilize FW in producing ethanol. Food waste is a non-value material easy to obtain at its source, so it has a potential for use as feedstock to produce a value-added product with a significant impact on both the economy and the environment.

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Figures

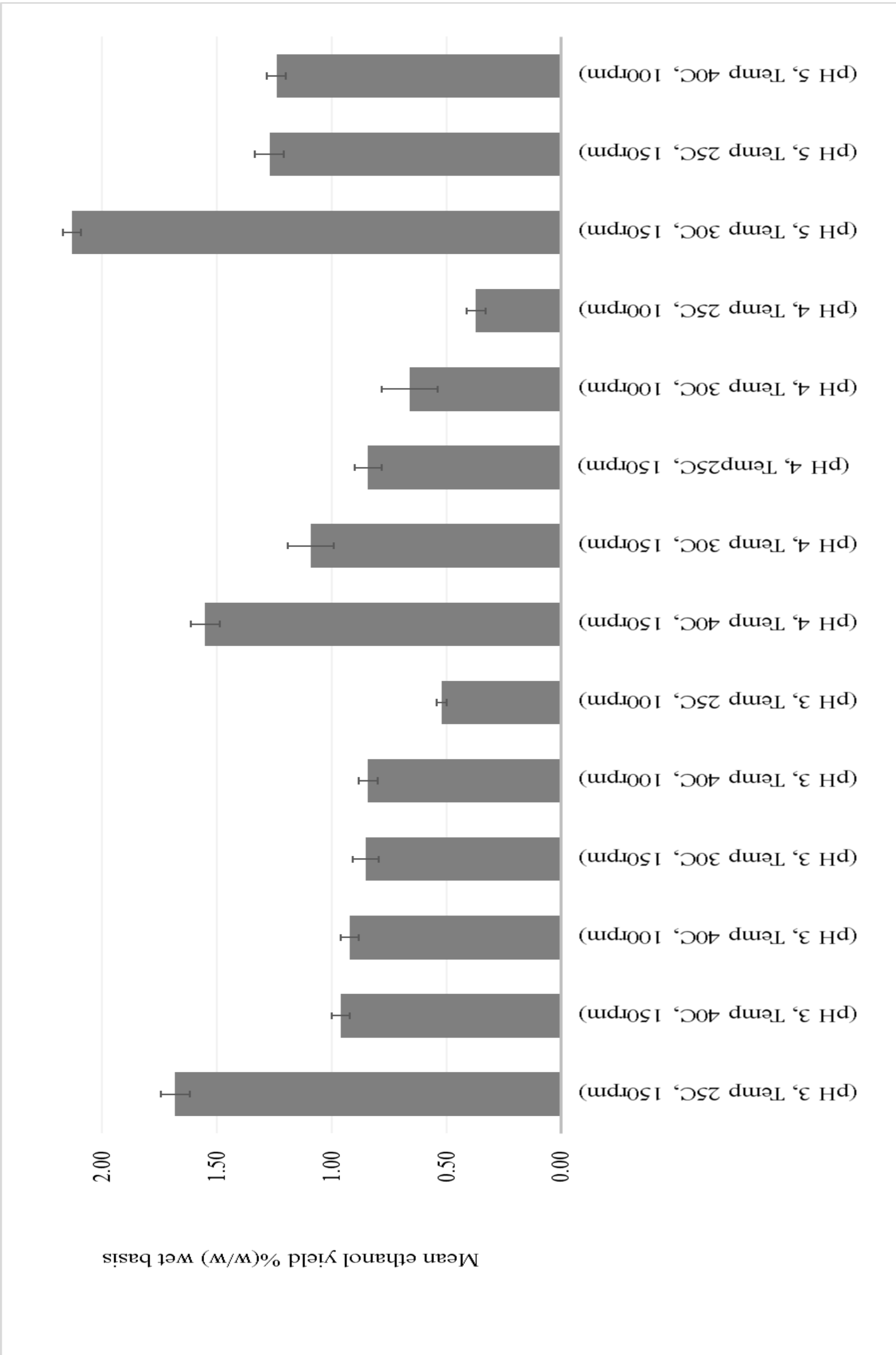

Figure 3-1 Ethanol yield (%) at different temperatures, agitation rate and pH. Error bars represent ± standard deviation.

Tables

Table 3-1 Design of experiment.

pH	Temperature (ºC)	Agitation (rpm)
3.0	25	100
3.0	25	150
3.0	30	150
3.0	40	100
3.0	40	150
4.0	25	100
4.0	25	150
4.0	30	100
4.0	30	150
4.0	40	100
4.0	40	150
5.0	25	150
5.0	30	150
5.0	40	100
5.0	40	150

Table 3-2 Mean ethanol yield (%) for all fermentation conditions. Values with different alphabet superscripts are significantly different at $P<0.05$ from all other conditions.

pH	Temperature (ºC)	Agitation (rpm)	Mean ethanol yield %(w/w) wet basis
5	40	150	2.23 ± 0.02^{a}
5	30	150	2.13 ± 0.04^{a}
3	25	150	1.68 ± 0.06^{b}
4	40	150	1.55 ± 0.06^{b}
5	25	150	1.27 ± 0.06^{c}
5	40	100	1.24 ± 0.04^{c}
4	30	150	1.09 ± 0.10^{cd}
3	40	150	0.96 ± 0.04^{d}
4	40	100	$0.92 \pm 0.04d^{e}$
3	30	150	$0.85 \pm 0.06d^{e}$
4	25	150	$0.84 \pm 0.06d^{e}$
3	40	100	$0.84 \pm 0.04d^{e}$
4	30	100	0.66 ± 0.12^{ef}
3	25	100	0.52 ± 0.02^{fg}
4	25	100	0.37 ± 0.04^{g}

Table 3-3 Analysis of effect test for ethanol production. (Significant effect at $P<0.05$).

Parameters	Degree of freedom	Sum of Squares	F ratio	Prob>F
pH	1	1.931	20.737	<0.0001*
Temperature	1	1.216	13.060	0.0008
Agitation	1	4.709	50.583	<.0001
pH * Temperature	1	0.939	10.086	0.0029

CHAPTER 4. TECHNO-ECONOMIC EVALUATION OF FOOD WASTE FERMENTATION ON VALUE ADDED-PRODUCT

Modified from paper will be submitted to the *Sustainability* journal.

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Abstract

Food waste (FW) continues to be a significant problem in the world, and most such waste will end up in landfills, causing environmental, ecosystem, and economic problems, and greenhouse gases emitted from decomposition of such waste will increase the effects of global warming. Leachate from disposal sites also has potential to contaminate nearby groundwater systems. Since the options available for diverting FW from landfills and finding other alternatives that can use this waste are challenging, this study was focused on determining the economic impact of FW fermentation in producing value-added products using techno-economic analysis (TEA). SuperPro Designer V9.0 simulation was used to model a commercial scale processing plant, and a TEA study was conducted for three scenarios: (a) a FW fermentation process producing hydrolysis enzymes and a 2-step distillation system, (b) a FW fermentation process without enzymes using a 2-step distillation system, and (c) a FW fermentation process without enzymes using a 1-step distillation system. Discounted cash flow analysis was used to estimate the minimum selling ethanol (MSE) price, producing the lowest MSE result of $2.41/gal of ethanol for scenario (b), shows

that, even without enzymes in FW fermentation, the product cost can be competitive compared to the other scenarios in this study. This project thus reflected a significant positive economic impact while minimizing the environmental footprint of a commercial production facility.

Introduction

The interest to find other option to reduce the dependency on fossil fuels makes it is more exciting and challenging. Ethanol was identified to be one of the best options to substitute gasoline with a less negative impact on the environment. Therefore, increasing biofuels production has gained more attention globally.

There are mandates in most countries to support biofuels development and consumption. For example, in the United States, the Renewable Fuel Standard (RFS2) under the Energy Independence and Security Act (EISA) has set the total renewable fuel production increased more than 100% from 2008 to 2022. Apart from that, cellulosic ethanol is predicted to be produced at least 16 million gallons in 2022 (EPA, 2017b). However, according to the Congressional Research Service (CRS) report, cellulosic biofuels has never met the mandate proposed by EISA. Shortage of cellulosic ethanol supply in the market has been a reason for the Environmental Protection Agency (EPA) to reduce the mandated target in the future (Bracmort, 2018).

Food Waste (FW) is categorized as one of the potential feedstock in cellulosic biofuel categories. It is abundant, rich with nutrient and zero cost (Meyer, Schmidhuber, & Barreiro-Hurlé, 2013). The FW generation is driven by various factors such as population growth, level of income, modernization, safety policy, and human behavior (Girotto & Alibardi, 2015; Thi, Kumar, & Lin, 2015; Uçkun Kıran, Trzcinski, & Liu, 2015). In 2015, the United

States had sent at least 76% of the total FW to the landfill followed by 18.6% for incineration and 5.3% for composting (EPA, 2018b). FW composition which rich with carbohydrates, protein, and lipid are easily to decompose by a microorganism and emit greenhouse gases (GHG) to the atmosphere. Methane gas (CH_4) is one of the potent gas in GHG which has a higher impact on global warming (EPA, 2018d; Ermolaev et al., 2015; Lopez, De la Cruz, & Barlaz, 2016). Furthermore, FW in the landfill could contribute a significant impact on the human health, ecosystem, diversity, land, and pollution as found by previous researchers (Noor, Yusuf, Abba, Abu Hassan, & Mohd Din, 2013; Woon, Lo, Chiu, & Yan, 2016). Additionally, FW also has a negative impact on the economy. For example, a larger area for the disposal site is required to load this waste, and the cost is significantly higher in an urban area. Other than that, the tipping fees are expensive based on the distance from the collection area and landfill area (de Lange & Nahman, 2015; EPA, 2018b; Guerrero, Maas, & Hogland, 2013a; Levis, Barlaz, Themelis, & Ulloa, 2010; Manaf, Samah, & Zukki, 2009).

Various studies related to FW analyses from university dining centers were reviewed for this study (Hafid, et al., 2015; Uçkun Kiran, Trzcinski, Ng, & Liu, 2014b; Uncu & Cekmecelioglu, 2011; Vavouraki, et al., 2013; X. Zhang & Richard, 2011), and Figure 4-1 shows average values of FW composition described in these studies. Even though the studies were performed in different regions, the results indicated glucose to be a principal component in FW followed by starch. Glucose is a fermentable sugar that can be directly consumed by Saccharomyces cerevisiae and converted into ethanol under anaerobic conditions. This type of yeast is widely used in the corn ethanol industry because it has a higher specific growth rate and productivity (Mohd Azhar, et al., 2017).

Because of its composition, FW is considered a potentially useful source for producing ethanol, and there are a few studies related to using FW fermentation in producing biofuels. Hafid, et al., (2017) used dilute acid and hydrothermal conditions to hydrolyze FW before the fermentation process to obtain a maximum ethanol yield of 0.42 g/g FW. Another study by Uncu and Cekmecelioglu (2011) achieved an optimum ethanol yield of 0.16 g /g dry matter using enzymatic hydrolysis (e.g., α-amylase, amyloglucosidase, cellulose, β-glucosidase) in the yeast fermentation process. That study showed the desirability of pre-treatment by either chemical or thermal means to enhance ethanol production, but such pre-treatment was unfortunately identified as being cost-intensive (Zheng, et al., 2009). For example, hydrolysis by dilute acid involves higher temperatures and pressures, increasing the utility and capital cost for a downstream neutralization system. Furthermore, enzymes are expensive, require more retention time, and have the potential to inhibit yeast fermentation (Pham, et al., 2015).

Alternatively, FW fermentation without chemical and thermal pre-treatment has found to be a potentially attractive approach. In Chapter 3, the experimental study achieved a maximum ethanol yield of 2.2% (w/w) on a wet basis without using any hydrolysis enzymes. This finding is higher than the result reported by Suwannarat and Ritchie (2015), given as ~1.5%, under the same feedstock and fermentation conditions.

Although there have been various studies to evaluate the potential of FW as ethanol feedstock, there have been no extensive studies on the full economic impact of such a process on a commercial scale (Karmee, 2016), so the focus of this study is to evaluate the economic impact of the ethanol production from FW process based on the three different scenarios illustrated in Figures 4-1 to 4-3. Scenario (a) uses fermentation conditions described in a study by Uncu and Cekmecelioglu (2011), while scenario (b) uses the experimental results reported in Chapter 3. In scenario (c), the ethanol conversion rate is similar to that of scenario (b) but with a modification on the separation system. Ethanol is considered to be the main product, while waste from the process is considered a co-product because both liquid and solid waste from the fermentation process have a resale value when used as organic liquid and bio-compost soil fertilizer. Since this waste also comprises a valuable nutrient that could enhance water retention in soil and provide carbon sequestration when used in the agricultural industry, liquid fertilizer and bio-compost could be expected to have a significant impact on the product value of ethanol.

Methodology

Process modeling

The conceptual process model for FW fermentation ethanol plant is simulated using SuperPro Designer V9.0. In this study, FW is assumed to have 78% moisture content with 45% glucose, 19% starch, 5% fiber (wet basis), and another trace element. The plant feedstock is supposed to be 2000 Mg/day. At present, FW is expected to have no cost for feedstock. The waste stream from the conversion process is considered as a by-product as mentioned in the previous section. In this conceptual simulation process, liquid and solid waste were separated using rotary filtration. The recommended moisture content of bio-compost is in the range of 40-60% by weight (Bertran, Sort, Soliva, & Trillas, 2004; Cornel Waste Management Institue, 1996). Therefore, in this study bio-compost is maintained to moisture content at 40% by weight to limit microbial activity.

Distillation is the common practice to separate ethanol from the fermentation followed by purification process through a molecular sieve. In this study, there are two different separation system using a distillation column was designed. For the scenario (a) and (b), the double distillation column was used. The first column is known as a beer column, while the second column has a combination between the stripping and rectifying column. Additionally, scenario (c) with one column distillation was conducted to evaluate the energy demand and cost requirement compared to scenario (a) and (b). The process flow diagram for scenario (a), (b) and (c) were shown in Figure 4-2, 4-3 and 4-4 respectively.

The mass and energy balance from the simulation model was used to size and quantity the equipment in the process. The total purchased equipment cost is taken from the software that indexed to 2018 dollars. The plant is having approximately 7900 operating hours per year.

Techno-economic assumptions

TEA is used to access the potential of commercial-scale plant FW to ethanol. The methodology for capital cost estimation is adapted from Peters et al. (2003). The installation factor for this study is 3.02, as it is a common factor for biorenewable facilities. The working capital cost is calculated from 15% of the fixed capital cost. The logistic of feedstock is important to determine the economically viable. According to Poliafico and Murphy (2007), a possible economic distance should be in the range of 9-16 miles. Thus, in this study 12 miles was used to calculate the transportation cost which contributes to the overall variable cost.

The discounted cash flow analysis was performed to evaluate the plant-gate price or known by minimum selling ethanol (MSE) price ($/gal). This value represents the lowest price for selling the ethanol to generate a net present value (NPV) of zero for the pre-determined internal rate of return (IRR). The IIR value was set to 10% to allow ethanol product cost to have a competitive price in the market (Brown & Brown, 2014). The working capital is assumed to be 15% of fixed capital investment. The capital cost and operational cost are taken from SuperPro V9.0 and used in the discounted cash flow analysis. Total project investment (TPI) is the total of capital, direct and indirect cost.

Most of the financial assumptions are adapted from NREL reports (Aden & Foust, 2009; Humbird et al., 2011; Short, Packey, & Holt, 1995; Tao et al., 2014; Wright, Daugaard, Satrio, & Brown, 2010). Table 4-1 shows the main economic parameters used in the discounted cash flow analysis to determine MSE in this study were adopted from the previous literature.

For scenario (a), enzymatic hydrolysis is used in the fermentation process to enhance the ethanol yield. Due to limited information on the exact price of industrial enzymes, therefore assumption for the similar cost from corn ethanol industry which equivalent to 3.35¢/gal ethanol (Hofstrand, 2018).

As mentioned previously, waste streams from the plant (e.g., liquid and solid) could potentially be used as organic fertilizer for agricultural. There is an available market to sell this product. Therefore, by considering selling all products, it could optimize the operational profit. The bio-compost is assumed to have a resale value of 8¢/lb based on the average organic fertilizer price in Iowa (National Compost Prices, 2006). Liquid fertilizer selling price is considered at conservative assumption which is 30¢/gal even in the real market; the rate could be higher than this. The utilities cost that being used in this study is presented in Table A-3, Appendix A.

Sensitivity analysis

Sensitivity analysis is performed by changed one parameter value while assumed the other parameters are constant. This approach is important to identify the variable that has a higher impact on MSE value. In this analysis, plant capacity (Mg/day), plant distance (miles), fixed capital cost ($), ethanol yield (%), enzymes price ($), liquid fertilizer ($/gal) and bio-compost ($/gal) credit value ($/gal) was selected to be evaluated. The range price for bio-compost is taken from National Compost Price (2006). The enzymes range cost is assumed to be from zero cost to 68¢/gal ethanol as found by Klein-Marcuschamer et al., (2012). For the other variables, the range ±30% was used to estimate MSE ($/gal) are at an optimistic, base case and pessimistic values for each case as suggested by previous studies (Brown & Brown, 2014b; NETL, 2011; Short et al., 1995). Other than that, the effects on IRR 10% and percent of equity with 8.25% interest rate and ten years loan also was conducted to seek the impact toward MSE. All selected parameters was shown in Table 4-2

Economies of scales

Economies of scale is an essential tool for business to look at the reduction of unit costs by increasing the production capacity. The main effect of economies of scale is to achieve the optimum plant capacity with the minimum cost of production. In this analysis, the FW rate value is designed from 10 Mg/day to 5000 Mg/day to project how price would change according to the expanding feedstock value.

Results and discussions

Economic analysis

The capacity of this plant is designed to have 2000 Mg/day of FW for all three scenarios. The mass balance obtained from the conceptual plant simulation shows that a case study (b) have a higher amount of ethanol production as expected. Table 4-3 shows the total installed equipment cost (TIEC), total project investment (TPI), annual utility cost, and ethanol production (gal/day) for the scenario (a), (b) and (c) as estimated from SuperPro simulation.

Scenario (a) had a higher in TPI and utility cost compared to other scenarios. It is because, in this simulation, there is two additional unit operation to convert starch into fermentable sugar as shown in Figure 4-2. These unit operations required different temperature where 95^{o}C and 55^{o}C were used for liquefaction and hydrolysis processes respectively. In fact, heating and cooling systems required more energy compared to other scenarios, thus led to higher annual utility cost. Utilities represent process inputs of heat transfer agent, electric power and water. Heat transfer agent demand in this processing plant are chilled water, cooling water and steam. For power demand, standard electric is used to supply energy and operate the equipment. The price for each unit energy is obtained from (EIA, 2017) and SuperPro Designer V9.0 software. Even though ethanol production is higher compared to other scenarios, it does not have an impact in decreasing the MSE value.

In a separation distillation column, there are two columns commonly used to gain higher purity of ethanol from the fermentation broth. The first column is designed to yield 55% (v/v) ethanol in the distillate, while the second column is a combination of stripping and rectifying systems gives a yield of 95-96 % (v/v) ethanol. Scenario (c) was designed with one column distillation as illustrated in Figure 4-4. This method is to assess the cost impact of one column distillation process for low concentration ethanol product. However, the distillate from the column required more units of molecular sieve to purify ethanol up to 99% (v/v). Therefore, scenario (c) required higher TPI than scenario (b) even though the ethanol yield was similar. This result shows that one column distillation is not economically viable.

Three major cost area were used in the discounted cash flow analysis to estimate the MSE ($/gal): total project investment (TPI), variable cost ($/yr) and fixed operating cost ($/yr). Variable cost consists of raw materials cost, transportation cost, utility cost while fixed cost consists of operating labor cost, laboratory cost, overhead, maintenance, local taxes, and insurances. Operating labor cost is wages for manpower who manage and operate the plant which estimated from the number of operators per shift as listed in Table A-4, Appendix A. Generally, a unit operation which involved with heat and complicated will require more operator to operate and maintain. Therefore, for the plant which has more unit operation are anticipated to have higher value in fixed cost.

Figure 4-5 shows the annual operating costs ($ MM/year), normalized average income tax and MSE ($/gal ethanol) for all scenarios. Operating costs are the expenses used by the plant operation on a continuous process associated with variable and fixed cost. From the graph, it can see that scenario (a) had the highest operating cost and capital depreciation compared to the other scenarios because of more unit operation and additional cost of enzymes.

MSE is the lowest ethanol cost capable of yielding an NPV of zero with 10% IRR. Higher production yield is not the critical factor that could influence the final product price. All cost incorporate with the process plant is counted to estimate MSE. Even the ethanol yield is higher in the scenario (a), but the estimated MSE value is 6.2% higher than scenario (b). This finding indicates that even without enzymes, FW has the potential to produce ethanol with lower MSE value. For scenario (c), the MSE value is the highest compared to others due to higher in TPI but lower in ethanol yield as mentioned before. Detailed discounted cash flow analysis and capital investment for all scenarios are presented in Table A-4, A-5, and A-6, Appendix A and Table B-1, B-2, and B-3, Appendix B respectively.

Sensitivity analysis

Figure 4-6 shows the sensitivity of minimum selling ethanol with 10% IRR to change in percent equity for all scenarios. The internal rate of return (IRR) is a method to estimate the profitability of the potential project. 10% value is the suggested assumption to makes the net present value (NPV) of all cash flows from this project is equal to zero. Equity is participation in or ownership of investor. From the graph, it shows that the changes in equity percent have a minor effect on the MSE.

Figure 4-7, 4-8 and 4-9 show the sensitivity analysis for each scenario. Variables such as plant capacity, fixed capital cost, enzymes price, co-product credit value, plant distance and ethanol yield have been identified to be evaluated the impact on MSE value.

Scenario (a) is illustrated in Figure 4-7. From the tornado chart, it clearly shows that the plant capacity fixed capital and enzymes price is the most sensitive variable that could influence the MSE value. As discussed above, by using enzymes, there will be additional process equipment and condition to enhance the production. Thus, it will affect the change in MSE value with small changes in the mentioned variable. Similar results from previous studies that found enzymes are not economically viable to be used in the process plant

(Klein-Marcuschamer et al., 2011a; Matsakas, Kekos, Loizidou, & Christakopoulos, 2014a; Pham et al., 2015).

Figure 4-8, shows the sensitivity analysis for scenario (b). From the result, the liquid fertilizer price and capital investment had the most impact on the minimum ethanol selling price. Increasing the liquid fertilizer credit value from 20¢ to 40¢ per gallons leads to a lowering of MSE from $3.86 to $1.10 per gallon ethanol. Additionally, decreasing of fixed capital cost at 30%, will decreasing the MSE value from $3.66 to $1.16 per gallons of ethanol.

Sensitivity analysis for a scenario (c) is shown in Figure 4-9. From the chart, plant capacity, fixed capital cost, and co-product credit value have a significant impact on MSE value. It is clearly seen that more than half of the variable are sensitive in estimating MSE value. Thus, it indicates that this plant is difficult to maintain profitability.

Economies of scale

Figure 4-10 shows the economies of scales for this process. It exists when the increasing size of plant capacity will be resulting in lower MSE. From the graph, there is a power relationship of –0.392 between MSE and plant capacity. It also indicates that with the feedstock rate varying between 10 and 5000 Mg per day, the MSE of ethanol ranges from $36 to $2.43 per gallon of ethanol. It clearly shows that the diseconomies of scale happen when the plant capacity increase to 3000 Mg per day. Thus, the size of plant capacity should not be larger than 3000 Mg daily to make the project economically feasible.

Conclusions

As previously discussed, although there are advantages for all scenarios in this study, discounted cash flow analysis indicated that scenario (b) showed a better MSE value as scenarios (a) and (c). The analysis also showed that ethanol produced without enzymes and with a 2-step distillation system exhibited a competitive MSE price of $2.41 per gallon, indicating that FW fermentation process without enzymes is significantly more practical and cost-effective than one with enzymatic assistance. Furthermore, to improve profitability, it is recommended to replace the distillation system with membrane distillation; a technology with low energy consumption and potentially effective approach by reducing the utility cost.

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Figures

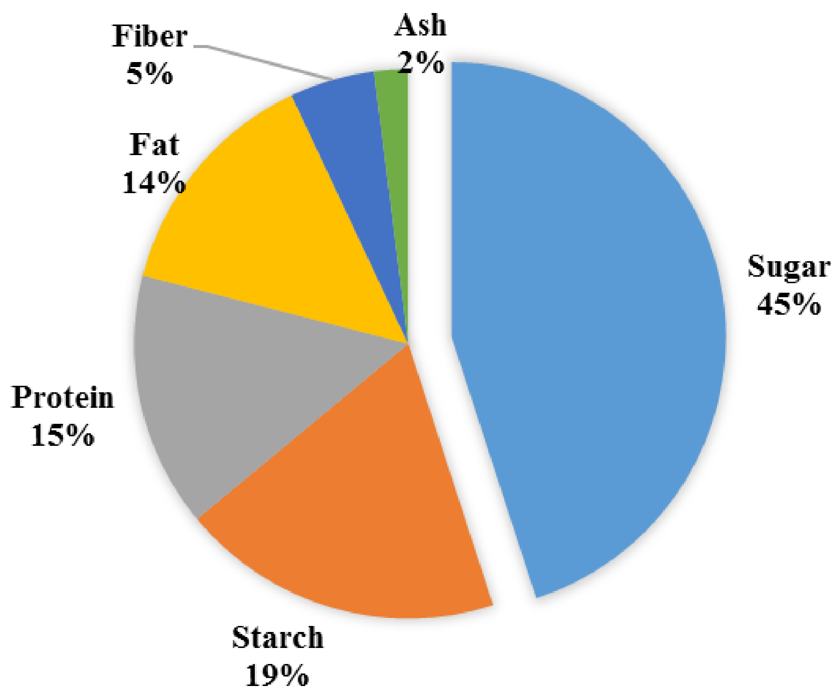

Figure 4-1 Average value of FW composition (% w/w wet basis)

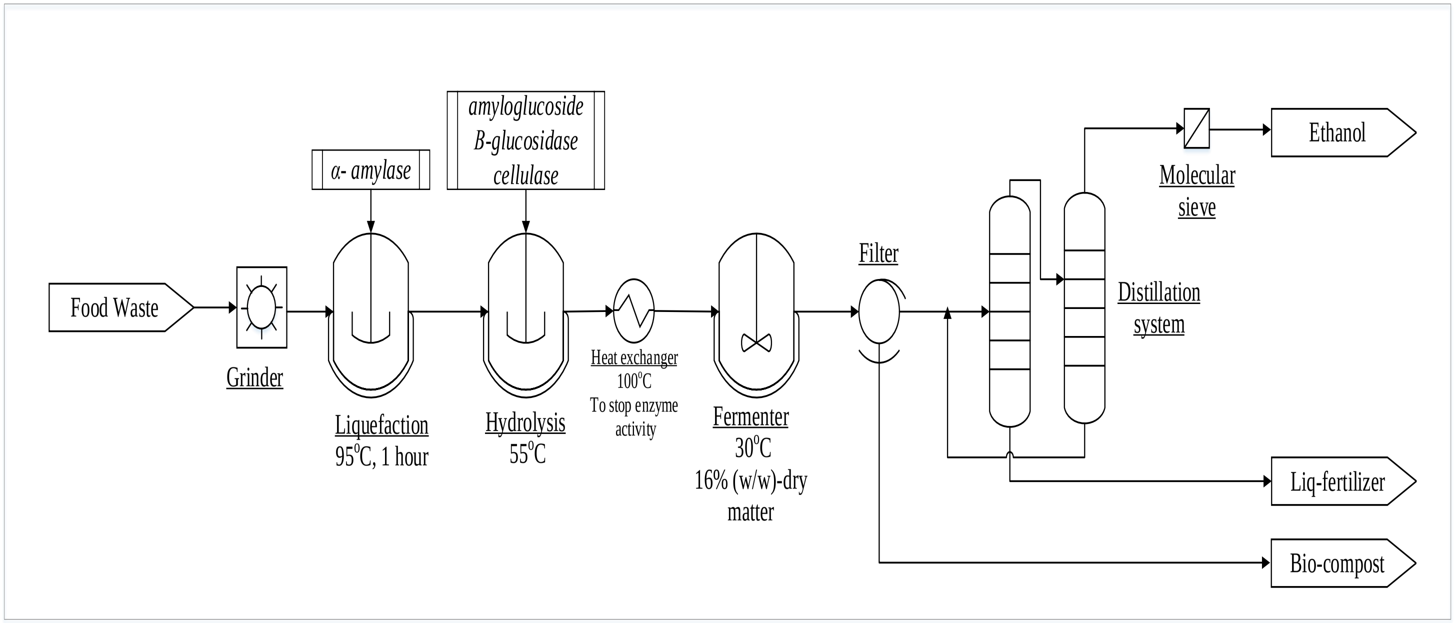

Figure 4-2 Process flow diagram of scenario (a) FW fermentation process with hydrolysis enzyme and 2-step distillation svstem.

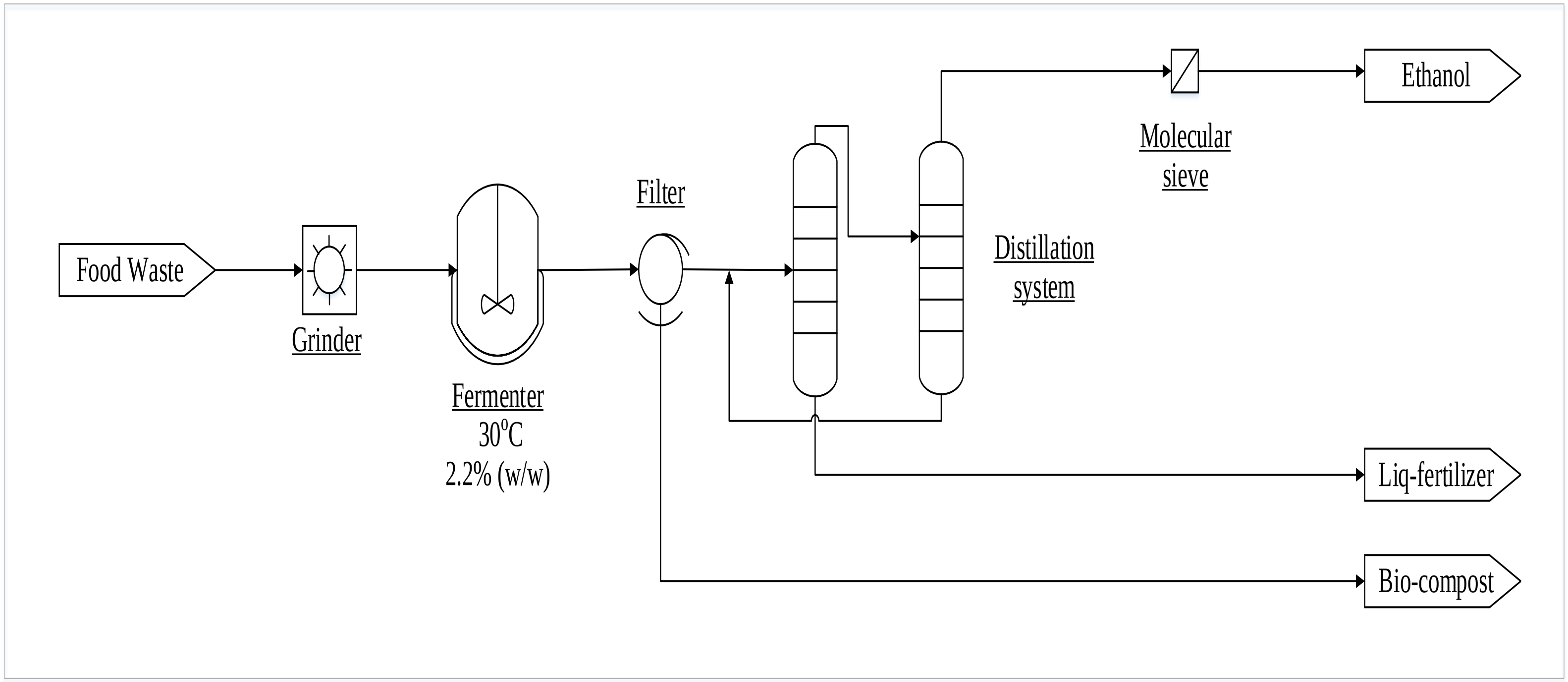

Figure 4-3 Process flow diagram of scenario (b) FW fermentation process without enzyme and 2-step distillation system.

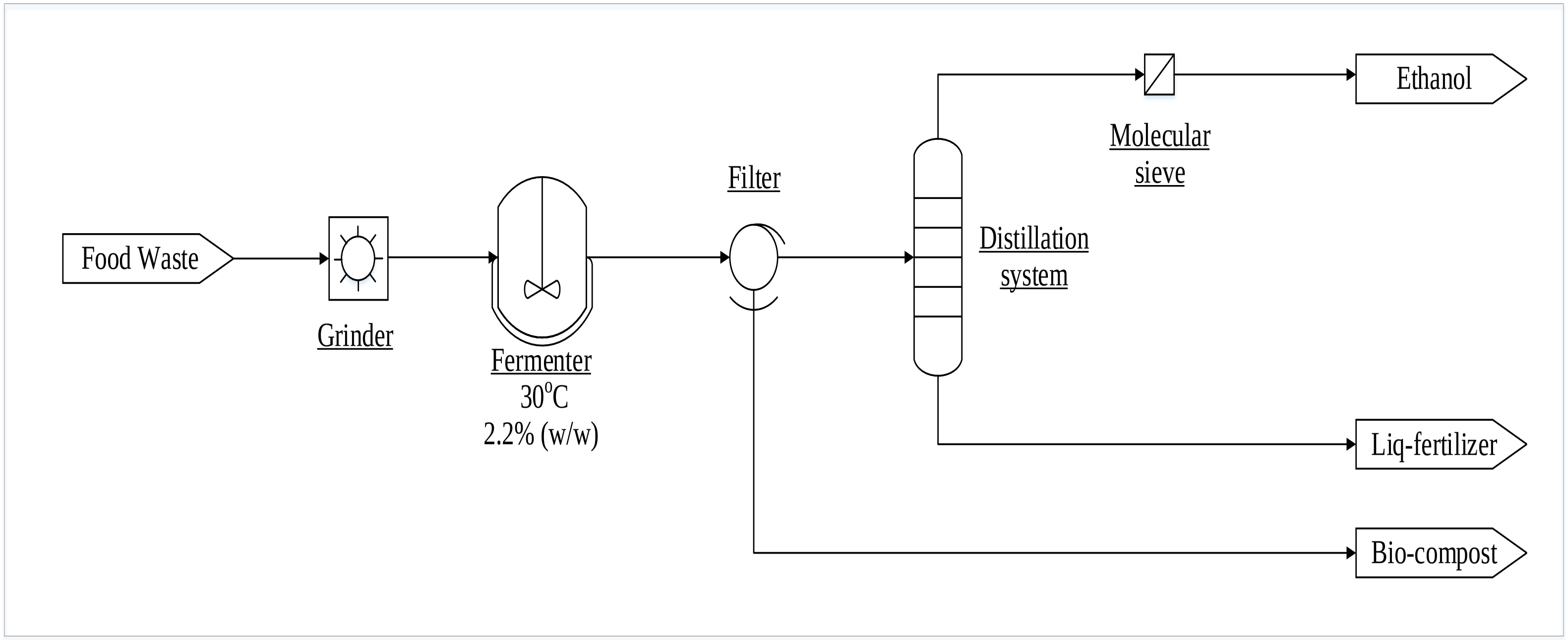

Figure 4-4 Process flow diagram of scenario (c) FW fermentation process without enzymes and 1-step distillation system.

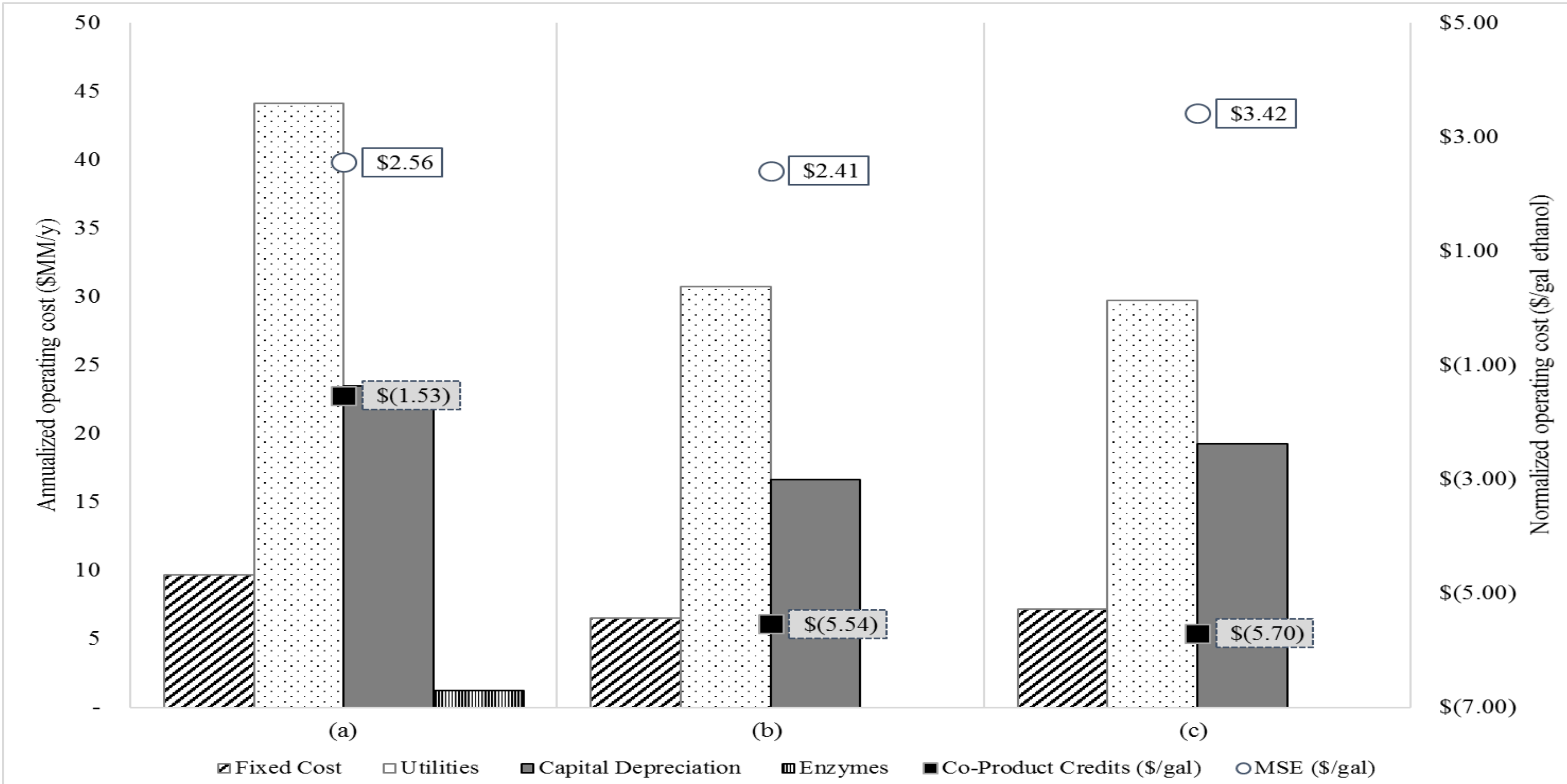

Figure 4-5 Annual operating cost ($ MM/y) and normalized operating cost ($/gal ethanol) for (a) FW fermentation with hydrolysis enzyme and 2-step distillation system, (b) FW fermentation process without enzymes and 2-step distillation system and (c) FW fermentation process without enzymes and 1-step distillation system.

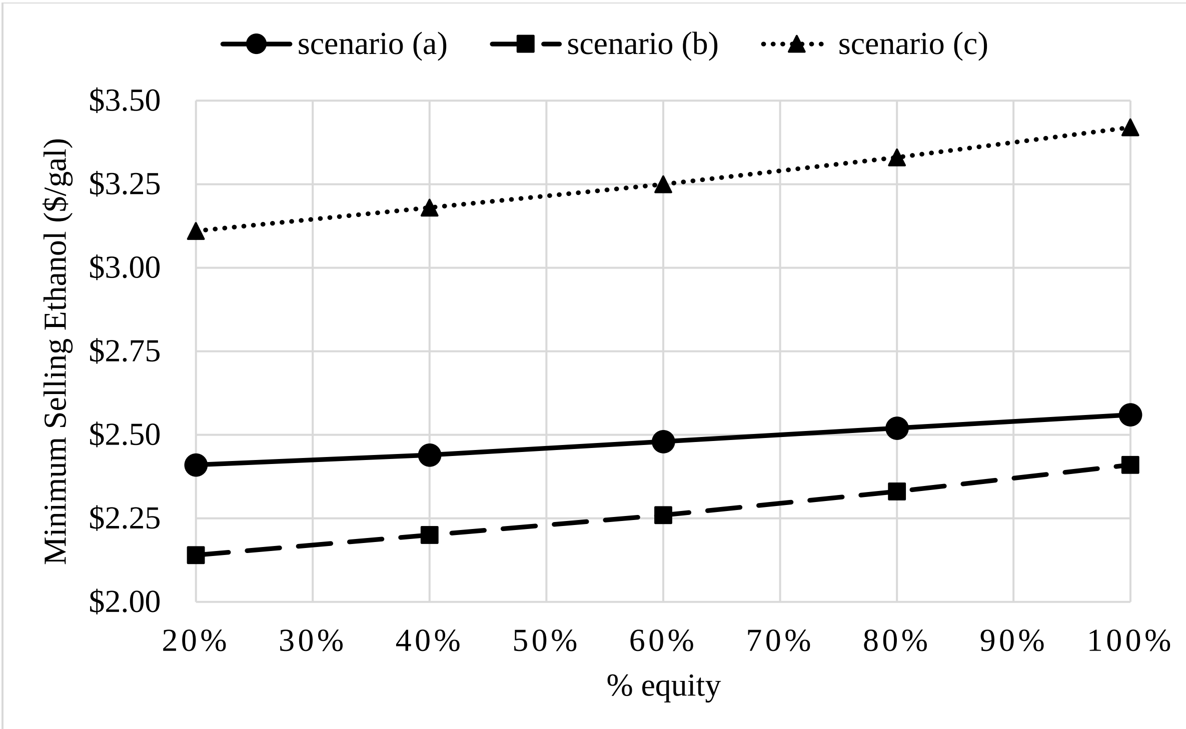

Figure 4-6 Sensitivity of MSE to IRR (10%) and percent equity (8.25% interest with a 10-year loan) for a scenario (a), (b) and (c).

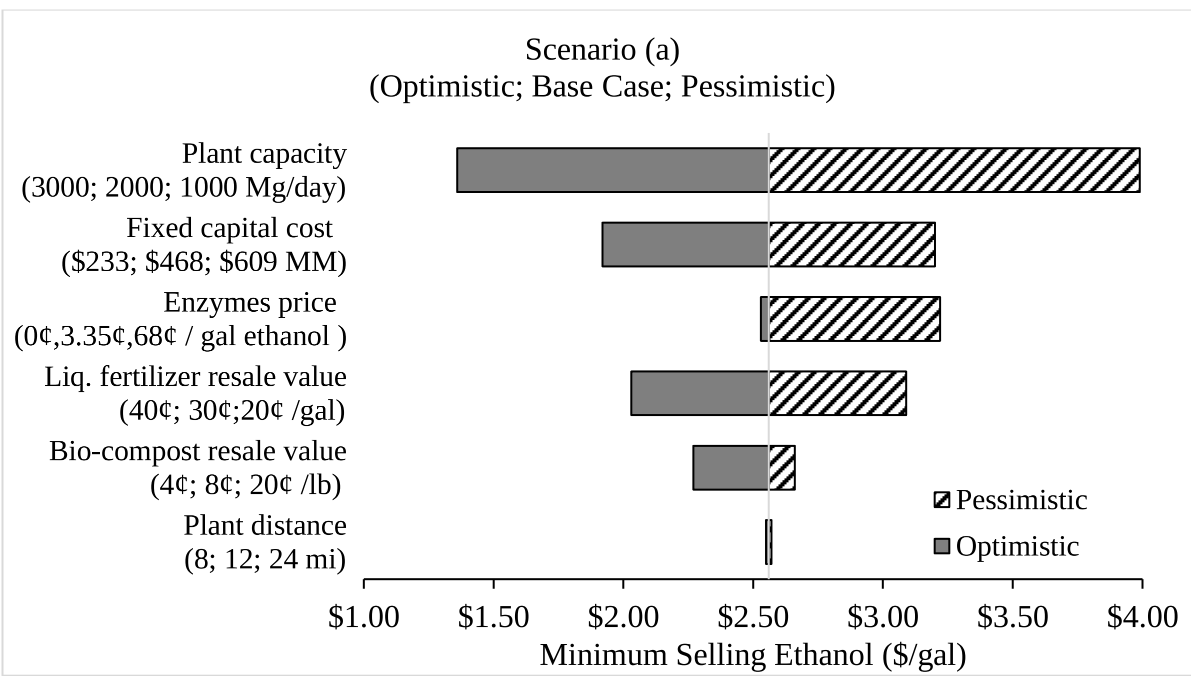

Figure 4-7 Sensitivity analysis of FW fermentation process with hydrolysis enzymes and 2-step distillation system. (Optimistic is the best case scenario simulation, pessimistic is the worst case scenario simulation).

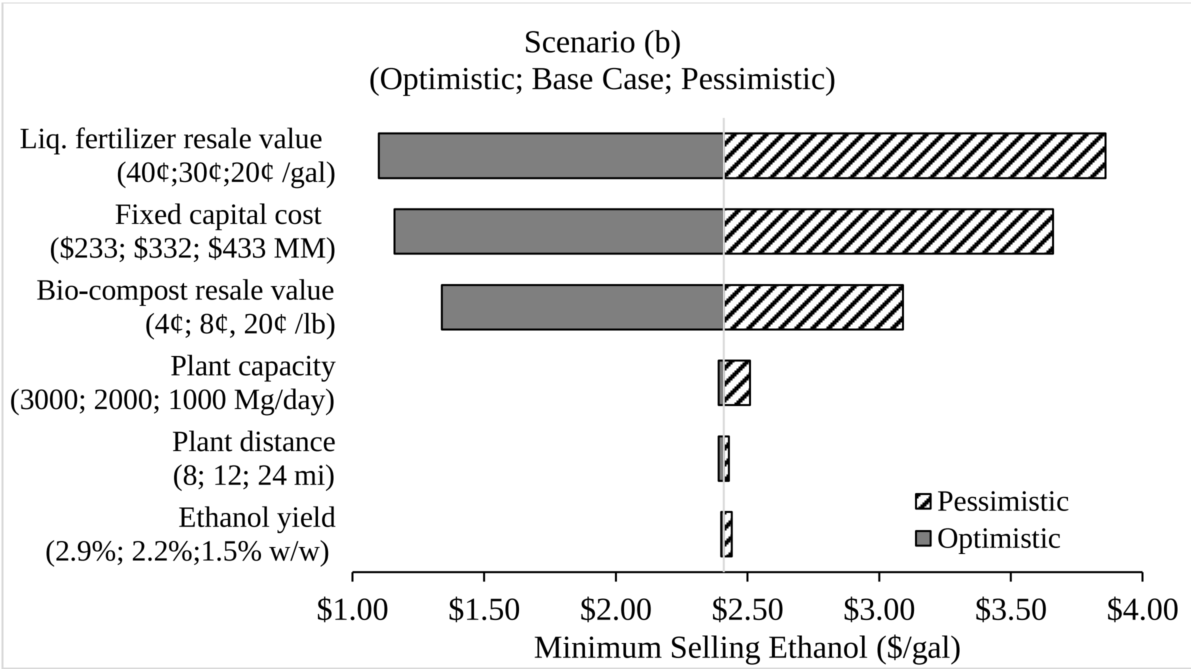

Figure 4-8 Sensitivity analysis of FW fermentation process without enzymes and 2-step distillation system. (Optimistic is the best case scenario simulation, pessimistic is the worst case scenario simulation).

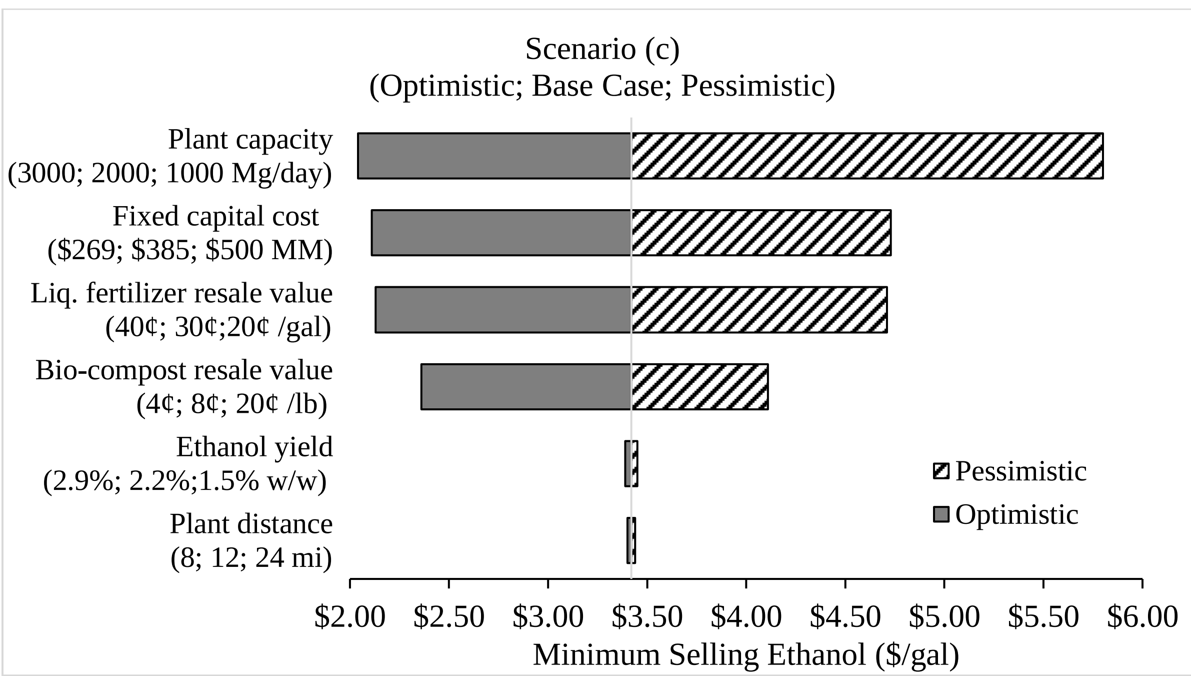

Figure 4-9 Sensitivity analysis of FW fermentation process without enzymes and 1-step distillation system. (Optimistic is the best case scenario simulation, pessimistic is the worst case scenario simulation).

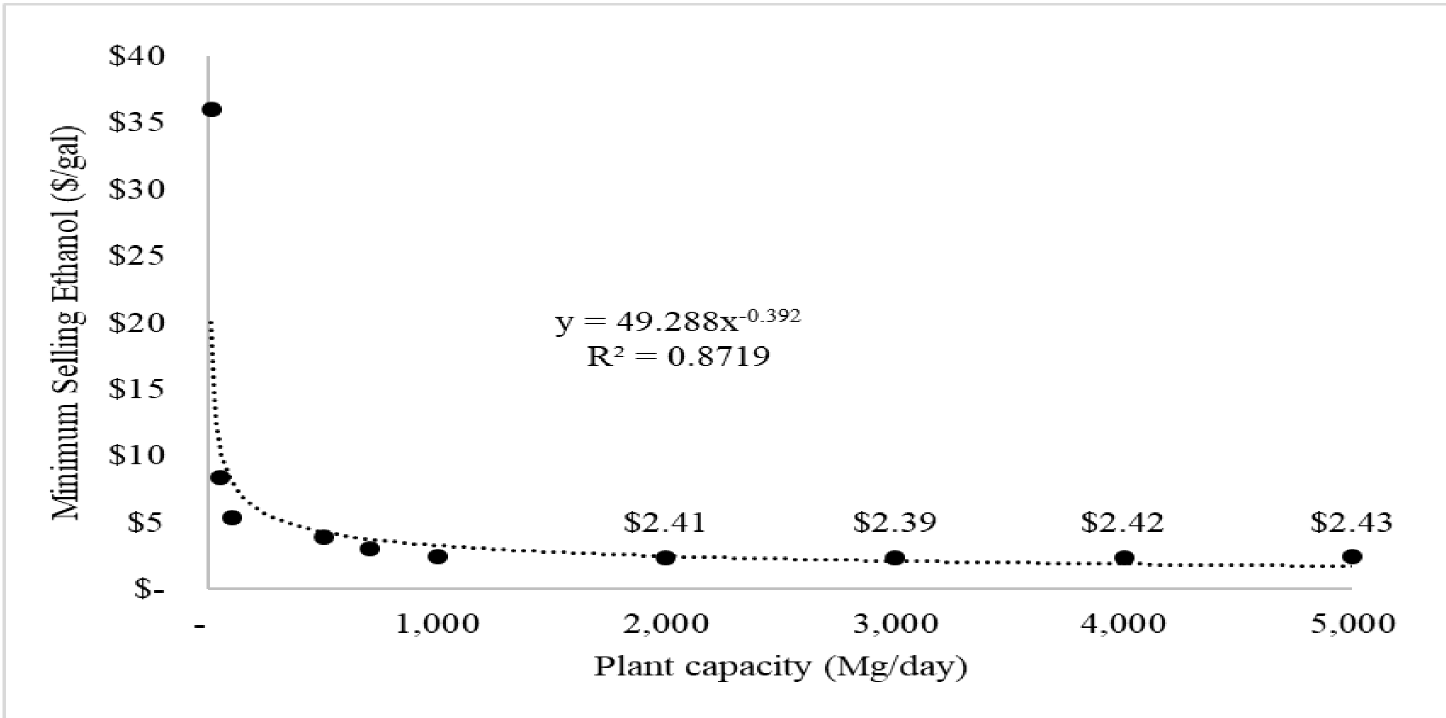

Figure 4-10 Economies of scale for scenario (b) FW fermentation process without enzymes and 2-step distillation system.

Tables

Table 4-1 Financial economic assumptions.

Parameter	Assumption
Plant capacity	2000 Mg/day
Plantlife	20 y
FW collection distance	12 mi radius
Equity	100% with 0 salvage value
The internal rate of return (IRR)	10% (Short et al., 1995)
Type of depreciation	Double-declining balance (DDB) 200% with seven years depreciation period.
Construction period	2.5 years with total capital investment spent at 8%, 60%, and 32% per year (years before the operation)
Startup time	Six months. During this period, revenues, variable operating costs, and fixed operating cost are at 50%, 75% and 100% of normal, respectively
Income tax rate	39%

Table 4-2 Sensitivity analysis parameters for all scenarios.

Parameters	Optimistic	Base case	Pessimistic
Ethanol yield (% w/w wet basis)	2.9	2.2	1.5
Plant capacity (Mg/day)	1000	2000	3000
Fixed capital cost ($MM)	-30%	Value estimated by SuperPro simulation	+30%
Plant distance (mi)	8	12	24
Liq. Fertilizer resale value (¢/gal)	40	30	20
Biocompost resale value (¢/lb)	20	8	4
Enzymes price (¢/gal ethanol)	0	3.35	68

Table 4-3 Economic analysis results (all results are in 2018 dollars).

Process variations (scenario)	TIEC ($MM)	TPI ($MM)	Annual utilities ($MM)	Plant size (Mg/day)	Ethanol production (MGPY)
(a) FW fermentation process with hydrolysis enzymes and 2-step distillation system.	301	545	44	2000	36.6
(b) FW fermentation process without enzymes and 2-step distillation system.	214	387	30	2000	14.5
(c) FW fermentation process without enzymes and 1-step distillation system.	247	447	25	2000	14.4

CHAPTER 5. ECONOMIC ASSESSMENT OF ETHANOL RECOVERY USING MEMBRANE DISTILLATION IN FOOD WASTE FERMENTATION

Modified from paper will be submitted to the *Renewable Energy* journal.

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Abstract

Ethanol is organic materials that have a high demand from different industries such as fuel, beverages and other industrial application. Commonly, ethanol was produced from yeast fermentation using sugar-crops as a feedstock. However, food waste (FW) was found to be one of the promising resources to produce ethanol because it contained a higher amount of glucose. Generally, column distillation was used to separate ethanol from the fermentation broth, but this operation is considered as an energy-intensive process. Additionally, membrane distillation is expected to be more practical and cost-effective because of less energy requirement. Therefore, this study aims to make a comparison of economic performance on FW fermentation with membrane distillation and a conventional distillation system using techno-economy analysis (TEA) method. A commercial-scale FW fermentation plant was modeled using SuperPro Designer V9.0 Modeling. Discounted cash flow analysis was employed to determine minimum selling ethanol (MSE) price for both systems at 10% of the internal rate of return. Results from this analysis showed that membrane distillation has a higher MSE than a conventional process, $6.24 and $2.41 per gallon respectively. Hence this

study found that membrane distillation is not economical to be implemented in commercial scale

Introduction

Food waste (FW) is considered as a growing problem in the world. This problem occurred throughout the food supply chain: from production to human consumption. In 2014, the United States generated 38 million tons of food waste yearly (EPA, 2018). There are various factors in FW generation such as spillage, inefficient storage facilities, spoilage, environmental change, and human behavior. Although this causes can be reduced by engineering control, however behavior and attitude is the most challenging factor to manage (Russell, Young, Unsworth, & Robinson, 2017).

The increasing of FW are expected to raise every year due to population and economic growth (Uçkun Kiran et al., 2014). GHG emission, climate change, water footprint, sanitation, health, ecological and economic are the effects caused by food waste (Levis et al., 2010; Sarika, David, Ricardo, & Kathrin, 2018). Landfilling is a convenient option as a FW disposal method. However, this method is not sustainable due to land limitation especially in an urban area (Guerrero, Maas, & Hogland, 2013). Thus, it is essential to find a new strategy for FW disposal and at the same time could reduce the environmental burden while producing a high-value product.

There is two method had been studied by the previous researcher which is through biochemical (e.g., fermentation, anaerobic digestion) and thermochemical (e.g., incineration, pyrolysis, and gasification). However, according to Pham et al. (2015), incineration, pyrolysis and gasification methods are not suitable because of the higher moisture content of FW and required higher energy to process. As for anaerobic digestion, higher capital cost and adverse environmental impact make this method not favorable. Hence, the fermentation method is considered as an effective method because of higher in glucose content which suitable for *Saccharomyces cerevisiae* to ferment into ethanol. Ethanol is an organic compound that has a demand in different industries such as in transportation fuel, cosmetic, pharmaceutical product, and household product.

As discussed in chapter 4, FW fermentation without enzymes and 2-step distillation system is found to be more economical in producing ethanol as the main product. From the results, this process has the lowest minimum selling ethanol (MSE) which is a $2.41per gallon. In this process, two column distillation was used to separate ethanol from the fermentation broth. This separation process is widely implemented in the ethanol industry.

However, the distillation column method is considered as an energy-intensive process which could increase the cost (Brown & Brown, 2014). At least 40% of the total energy consumption in ethanol production is coming from the distillation process (E. Nagy & Boldyryev, 2013). Several methods are recommended to substitute the distillation process. The membrane provides an alternative option, either using hydrophobic or hydrophilic membranes to separate ethanol from the fermentation broth. Membrane distillation (MD) is one of the emerging technology that has gained more attention from researchers and industries. In this process, the separation process can occur below the average boiling point of the solution. Addition to that, the membrane performance is varies based on membrane selectivity, operational condition, types and size of polymers. (Lewandowicz, Białas, Marczewski, & Szymanowska, 2011). Therefore, it would be considered to be more efficient, easy to operate, and low energy requirement (Baeyens et al., 2015; Drioli, Ali, & Macedonio, 2015; Fan, Xiao, & Li, 2016). Hence, MD it is expected to improve the process of economic performance.

In this study, the hydrophobic porous membrane was used as the MD method. The driving force in this system is maintained by the differential pressure of both sides of the layer due to the temperature difference. The general schematic diagram of membrane operation is shown in Figure 5-1. The feed stream temperature is suggested to be higher so that the desired components could diffuse through the membrane. According to Baeyens et al. (2015), the permeate flux increase significantly with increasing feed temperature in a range of 37^{o}C to 61^{o}C.

Therefore, the main focus of this study is to make a comparison of economic performance on FW fermentation with membrane distillation and conventional distillation column in the ethanol separation process. Techno-economic analysis (TEA) will be used to estimate the minimum selling ethanol price (MSE) per gallon. The economic performance for the distillation column was discussed in the previous chapter.

Methodology

Process modeling

The food waste composition are illustrated in Figure 5-2 and the fermentation process in open anaerobic condition with ethanol yield as 2.2% (w/w) wet basis without any enzymes was modeled. The yield of conversion is taken from the experimental study as reported in Chapter 3. MD was designed as the ethanol separation process using SuperPro Designer V9.0 for evaluating the plant performance on a commercial scale. The daily plant feedstock is assumed to be 2000 Mg/day at zero cost. The moisture content of solid waste from this separation process will be maintained at 40% by weight to control the microbial activity.

MD was used in this processing plant because this process is expected to have less energy consumption compared to the distillation system. In this simulation, the fermentation broth will be heated to 37^{o}C for obtained permeate flux at 0.32 g/m^{2}s (Baeyens et al., 2015).

The size and quantity of equipment, utilities and energy consumptions, transportation cost, labor and raw material needed are determined by mass and energy balance from the simulation. The plant is expected to operate at least 7900 hours per year. The overall process flow is illustrated in Figure 5-3.

Techno-economic assumptions

In this study, a list of assumption was made for the operation process and economic evaluation. Equipment purchased cost is taken from developed models in SuperPro Designer V9.0 and indexed to 2018 dollars. Method to calculate the project investment expenditure are adopted from Peter et al. (2003) which commonly accurate within 30%. Addition to that, 3.02 installation factor is used because it is a common assumption factor for biorenewable facilities plant (Brown & Brown, 2014b). Discounted cash flow analysis spreadsheet was used to estimate the MSE price ($/gal) with a zero of net present value (NPV) and a predetermined internal rate of return. The main assumptions are listed below, and the detailed values provided in Appendix A

- Plant capacity: 2000 Mg/day
- Plant feedstock: FW with 78% moisture content
- Plant distance: 12 mi radius (Poliafico & Murphy, 2007)

- Plant life: 20 y
- The internal rate of return (IRR): 10% (Short et al., 1995)
- Equity financed: 100%
- Plant depreciate: 7 y with 200% double declining balance (DDB)
- Contingency factor: 20% from total installed equipment and indirect cost
- Construction period: 2.5 y with total capital investment spent with 8%, 60% and 32% for first, second and third year respectively.
- Startup period: 6 months with considering 50% of revenues, 75% variable cost and 100% fixed expenses will be achieved.

As mentioned previously, bio-compost will be considered as co-product and can be sell as organic fertilizer in the agricultural market to optimize the operational profit. The selling price of bio-compost is assumed to be 8¢/lb based on the average organic fertilizer price in Iowa (National Compost Prices, 2006). The number of operators per each equipment is listed in Table A-4, Appendix A.

Economies of scale will be performed in this study to evaluate the reduction of the product value as increasing daily feedstock volume from 10 Mg to 5000 Mg. From this analysis, the range of optimum feedstock value with the lower MSE value will be estimated for the future study.

Sensitivity analysis

Further analysis is required to identify which parameter has the most significant impact on MSE value. A sensitivity analysis is a method by modifying one parameter value while maintained others. Table 5-1 shows the sensitivity analysis parameters selected for this analysis. These parameters are identified as a powerful impact on plant economic performance.

Results and discussions

Economic analysis

This plant is designed to have a feedstock capacity at 2000 Mg/day of FW. The mass and energy balance is obtained from the simulation result. From the discounted cash flow analysis the MSE price was estimated to $6.24 per gallon with yielding an NPV of zero and 10% IRR. Detailed of discounted cash flow analysis for FW fermentation with membrane distillation are presented in Table A-7, Appendix A.

As detailed in Table B-4, Appendix B, this plant has a value for total installed equipment cost (TIEC) and total project investment (TPI) of $375 MM and $677 MM respectively. In addition to that, annual utility cost ($/yr) and labor cost ($/yr) demand amount as $26 MM and $1.1 MM correspondingly. From chapter 4, FW fermentation without enzymes and two distillation column have the best economic performance. If compared with this system, the distillation column is better than membrane distillation regarding capital investment as illustrated in Figure 5-4. Theoretically, the membrane has a limited lifespan and expenses that makes it not practical to be used in commercial scale.

Moreover, more unit of membrane distillation is required due to the fouling factor. The accumulation of deposit on the surface will clog the pore and reduce the permeability. Thus, it could reduce the separation process efficiency.

Higher energy consumption is the main reason that distillation column is not favorable. In this analysis, energy is counted in utility cost which considered as standard electric power, steam, water, cooling, and chilled water. The price for each unit of utilities is shown in Table 5-2. Price for electricity and water are taken from EIA (2017), while for steam, cooling and chilled water are taken from the default setting in the SuperPro Designer V9.0 software.

Results from the economic analysis showed that membrane distillation has the lowest utility price, compared to the distillation column. This finding supports that distillation column required more energy compared to the membrane. However, annually fixed cost membrane distillation costed 36% more than the distillation column. As mentioned above, the membrane needs more unit, thus will increase the labor, maintenance and operating cost. The comparison of both systems clearly shown in Figure 5-5.

Economies of scale for membrane distillation study is represented in Figure 5-6. From the graph, there is a power relationship of -0.268 between MSE and feedstock size. It also shows that with the feedstock rate varying between 10 and 5000 Mg per day, the MSE of ethanol ranges from $40.62 to $6.39 per gallon of ethanol. It clearly shows that the diseconomies of scale happen when the plant capacity increase to 3000 Mg per day. Thus, the size of the feedstock input value should not be larger than 3000 Mg daily to make the project economically feasible.

Sensitivity analysis

Figure 5-7 shows the sensitivity analysis for the membrane distillation separation process. From the tornado chart, it indicates that fix capital cost is the most influential parameter in estimating the MSE value. The increasing amount of capital cost from $407MM to $757MM will elevate the MSE value by 88%. As discussed previously, membrane distillation has a higher capital and operational cost because more separation unit is required with the higher cost of a membrane.

Conclusions

The techno-economic analysis evaluates the product cost of FW fermentation with two differences of separation process; membrane and distillation system. Based on the mass balance, both of the methods could potentially recover ethanol up to 97% with further purification system. The membrane is less energy demand, but it has higher capital and operational cost. The result from a discounted cash flow analysis showed that the MSE for membrane distillation is higher over the conventional distillation system with estimated value are \$6.24 /gal and \$2.41/gal respectively. The negative economic impact of membrane distillation is one of the most challenging factors and makes it not favorable.

Similarly, the selectivity membrane materials are expensive and have a shorter lifespan and not being considered in this study. Thus, it could increase the capital and maintenance cost. Overall, the total plant investment and annual fixed cost were the factors driving the increase in product cost.

Sensitivity analysis is the method to find the parameters that strongly impact the estimation of MSE value. The variability of capital cost at ±30% would result in MSE in range of \$4.32 to \$8.12 per gallon.

In this study, the fermentation process was modeled with a batch condition and further continue with the separation process. At this process condition, membrane distillation was found to not be economically viable due to reasons discussed above. However, there is abundant room for further research that can be done in the future to reduce the MSE. For example, a modification can be considered to change the product harvesting from batch to continuous using recycling stream to enhance the separation process.

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Figures

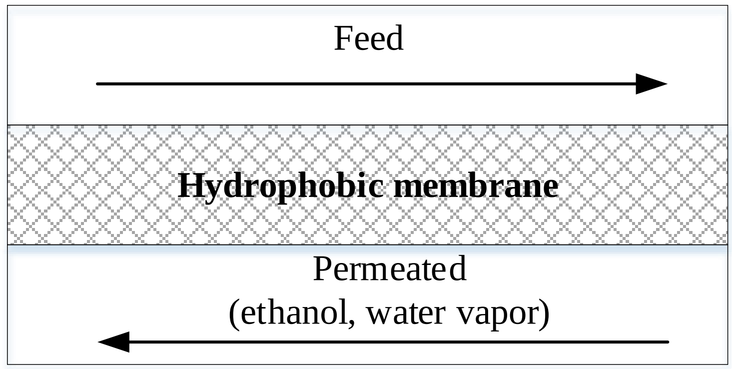

Figure 5-1 Schematic diagram of the membrane distillation process.

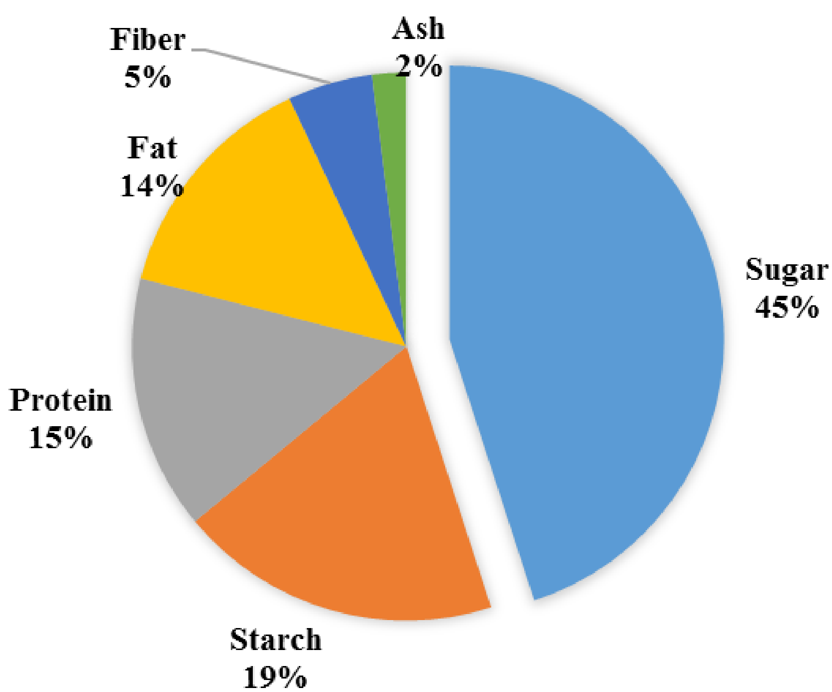

Figure 5-2 Average value of FW composition (% w/w wet basis)

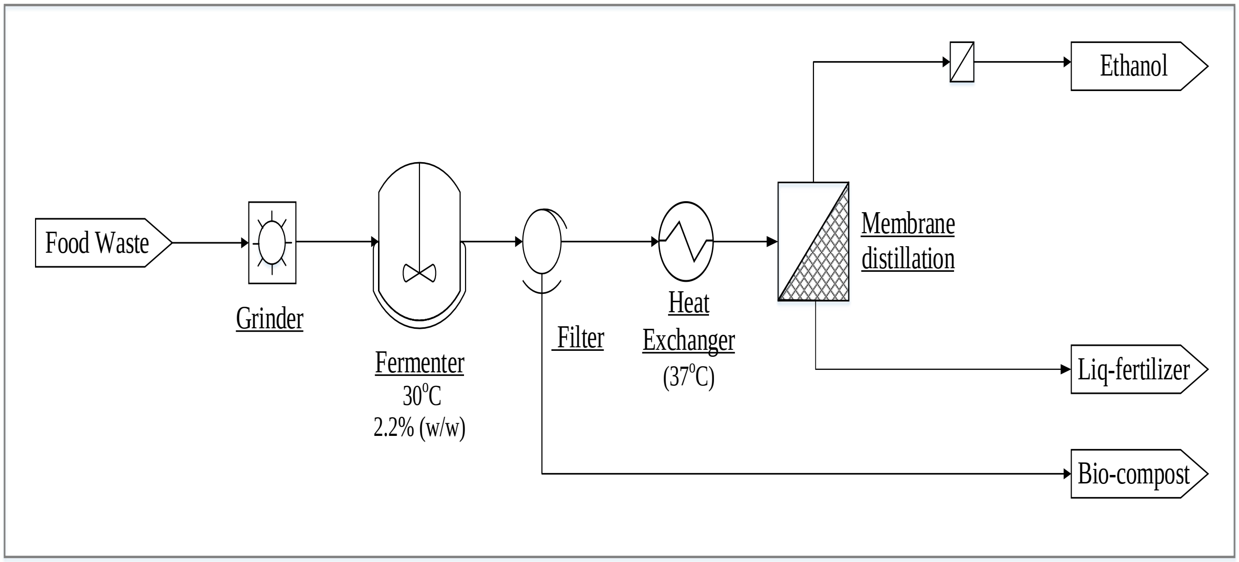

Figure 5-3 Process flow diagram of FW fermentation with membrane distillation separation process.

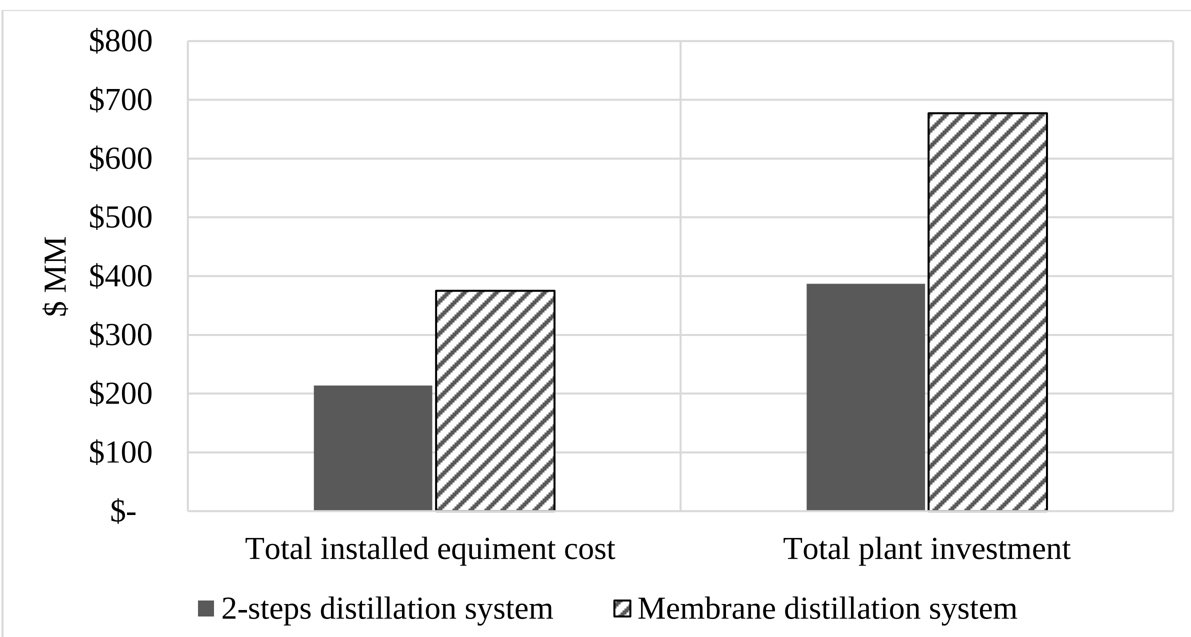

Figure 5-4 Comparison of capital investment of FW fermentation with 2-step distillation system and membrane distillation separation process.

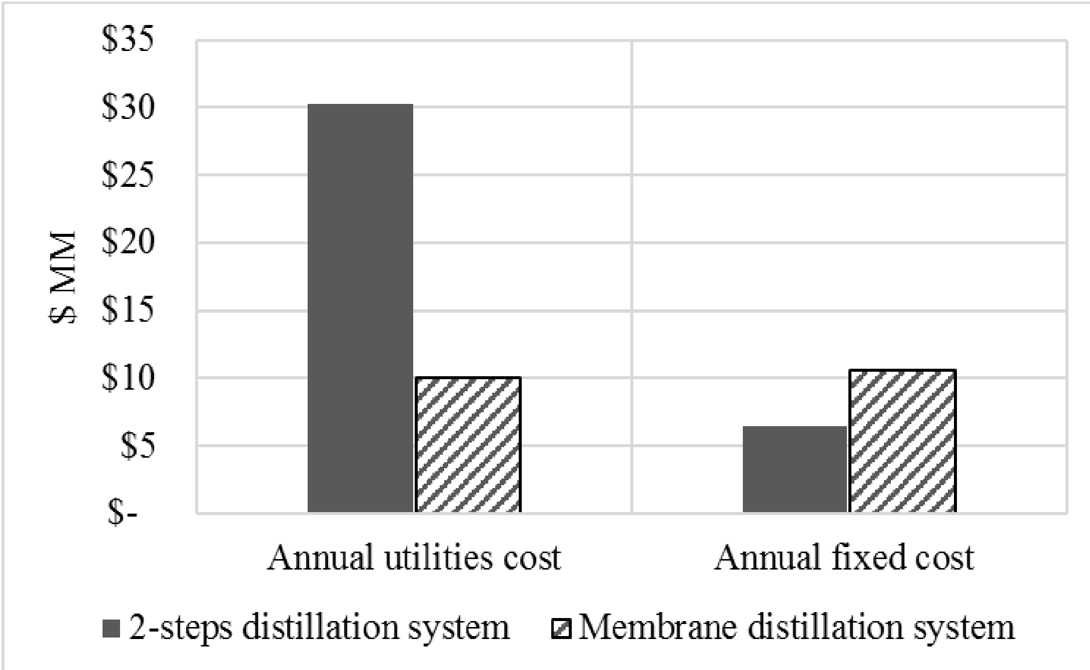

Figure 5-5 Comparison of variable and fixed cost of FW fermentation with 2-step distillation system and membrane distillation separation process.

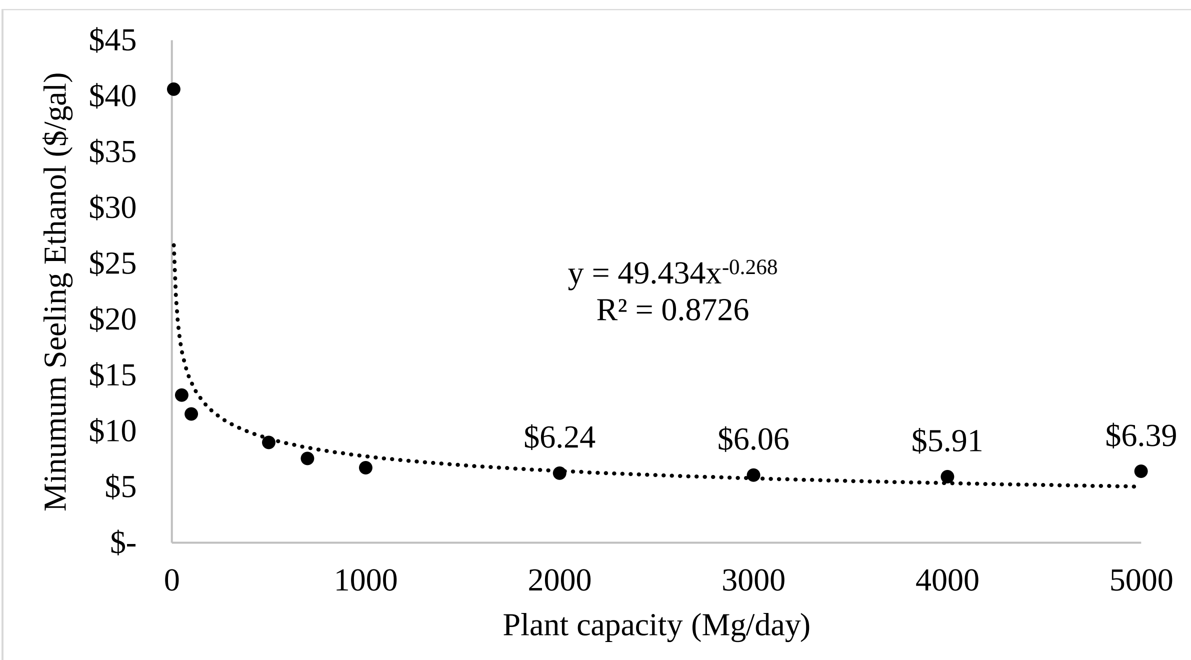

Figure 5-6 Economies of scale of FW fermentation with membrane distillation separation process.

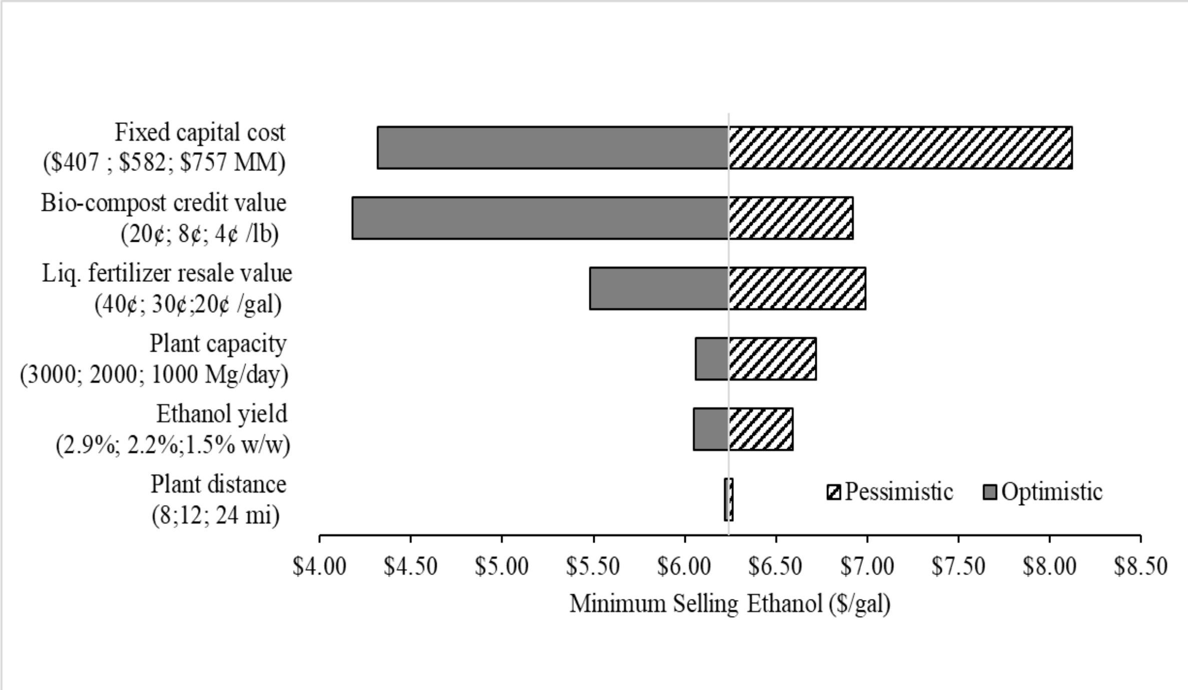

Figure 5-7 Sensitivity analysis of FW fermentation with membrane distillation separation process. (Optimistic is the best case scenario simulation, pessimistic is the worst case scenario simulation).

Tables

Table 5-1 Sensitivity analysis parameters for FW fermentation with membrane distillation separation process.

Parameters	Optimistic	Base case	Pessimistic
Plant distance (mi radius)	8	12	24
Bio-compost resale value (¢/lb)	20	8	4
Plant Capacity (Mg/day)	1000	2000	3000
Liq. Fertilizer re-sale value (¢/gal)	40	30	20
Ethanol yield (% w/w) wet basis	2.9	2.2	1.5
Fix capital cost ($MM)	407	585	757

Table 5-2 Utility prices (EIA, 2017).

Utility component	Prices
Electricity (¢ /Kwh)	5.5
Water (¢/gal)	0.350
Steam ($/Mg)	12.00
Cooling water ($/Mg)	0.05
Chilled water ($/Mg)	0.40

CHAPTER 6. ECONOMIC EVALUATION OF COMBINED HEAT POWER (CHP) INTEGRATED WITH FOOD WASTE BASED ETHANOL PRODUCTION PLANT

Modified from paper will be submitted to the *Biomass & Bioenergy* journal.

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Abstract

The concern of food waste (FW) impact on the environment, society and economy, has triggered the researcher to find an alternative way to utilize it. FW is rich with glucose and has the potential to be converted into value-added products such as ethanol. Ethanol is organic materials that have a high demand from different industries such as fuel, beverages, pharmaceutical, and other industrial application. FW fermentation in producing ethanol is a promising method and expected to receive a positive impact on the economy. However, the product price is probably challenging to compete with corn ethanol due to low yield and inconsistency of FW composition. Thus, to increase the profitability, conventional plant integrated with combined heat and power (CHP) system could be a great combination and was conducted in this study. Solid waste stream from the process can be converted into energy and could reduce the utility cost. Therefore, the main focus of this study is to evaluate the economic impact of this integrated system by estimate the minimum selling ethanol (MSE) price using techno-economic analysis (TEA). Results from this analysis showed that the MSE value for this integrated system was $1.88 per gallon. This study suggests that the

integrated system with CHP was found to be more economical and attractive to be implemented in commercial scale.

Introduction

Every year, the world has generated food waste (FW) about 1.3 billion tons through supply food chain stages including at the consumer level. Addition to that, this waste is expected to increase by several factors such as managerial and technical limitation, global population, modernization and living style (Aschemann-Witzel et al., 2015; Gustavsson et al., 2011). For instead, in the United States, 76.1% of the FW will be sent to the landfills as a final destination (EPA, 2018a). Furthermore, FW could lead to a various problem such as to environment, social, ecosystem and economy (Papargyropoulou, Lozano, K. Steinberger, Wright, & Ujang, 2014).

Prevention is the best option in the FW management hierarchy, followed by recycling, energy recovery, and disposal. Thus, by considering the amount of valuable nutrient in the FW, recycling using the biological platform in producing other value-added products would be a great approach. This method is expected to receive a good impact on economic and environment compared to the thermochemical technology.

Anaerobic digestion (AD) and fermentation are relatively a matured technology that could produce energy such as biogas and ethanol respectively. However, according to Pham et al., (2015), an AD method will add a negative impact on the environment and more costly.

A study from Chapter 4 found that ethanol conversion from FW without enzymes has good potential in economic perspective. Even though the distillation column was identified as an energy-intensive process, but the MSE value is lowest than the membrane separation process. The economic analysis and the results for this comparison were presented in detail in chapter 5. From the economic analysis, the minimum selling ethanol (MSE) price for FW fermentation without enzymes and 2-step distillation system was found to be $2.41/gal. This value is in between corn ethanol price and cellulosic ethanol. However, the ethanol price from FW fermentation is expected to be more economical if the production process could integrate with combined heat process (CHP) by producing in-site energy to minimizing the utility cost.

CHP is an integrated system that could produce electric power and steam on site. The advantages of embedded on site the plant are to avoid losses in distribution and transportation from the electrical power grid. The CHP is not considered as technology, but a method in applying technologies. Therefore, the implementation of this system could increase energy efficiency, minimize the emission, reduce utility cost and promote sustainable development. Various studies have been suggested to use the integrated system in the ethanol fermentation plant due to advantages as mentioned above (Daianova, Dotzauer, Thorin, & Yan, 2012; Dias, Lima, & Mariano, 2018; Eriksson & Kjellström, 2010; Raj, Iniyan, & Goic, 2011).

The concepts of CHP is direct combustion of the solid waste stream that will convert chemical energy into heat energy. The consistent of the heat source from the boiler will turn water into high-pressure steam. By using the Rankine cycle principle, the steam turbine can produce electricity. The backpressure steam turbine is commonly used in the industrial plant because of the low capital cost, simple configuration and high efficiency (DOE, 2016). The steam exhausts from the system will be recovered and use directly to a process and steam distribution. The biomass moisture content of biomass should be in the range of 15-55% before can be directly burnt in the combustion system (Pirouti, Wu, Ekanayake & Jenkins, 2010). Detail of the overall process is shown in the schematic diagram in Figure 6-1.

In this study, FW fermentation without enzymes integrated with CHP process is modeled. The process model and conditions are based on the previous chapter with additional energy cogeneration model. The primary target of this study is to evaluate and compare the economic performance between with and without the integrated system. The techno-economic analysis will be performed to estimate the minimum selling ethanol ($/gal) and sensitivity analysis to identify the impact of processing parameter on economic feasibility.

Methodology

Process modeling

SuperPro Designer V9.0 software will be used to simulate the integrated conceptual fermentation plant as mentioned above. The daily plant feedstock is supposed to be 2000 Mg and assuming at zero cost. The main product from FW fermentation process is ethanol while liquid fertilizer and bio-compost are considered as a co-product. From the previous chapter, both liquid and the solid waste stream will be sold for other industry to maximize the profit. However, in this study, another option to analyze with utilizing bio compost to generate heat and power by using the CHP system. The moisture content of bio compost is maintained at 40% by weight before combusted in the burner. The chemical energy will be converted into heat energy to generated steam in the boiler. High-pressure steam drives the steam turbine which satisfies the thermodynamic cycle that changes heat to mechanical works. The turbine drives the generator and finally generates electric power and then will be used back in the facilities. In this study, assume that no surplus electricity can be sold to the grid.

Furthermore, the exhaust steam from the steam turbine will be captured and use for the heating system. The process diagram flow is illustrated in Figure 6-2. Other than that, the size and quantity of equipment, utilities and energy consumptions, transportation cost, labor and raw material needed are determined by mass and energy balance from the simulation. The plant is expected to operate at least 7900 hours per year.

Techno-economic assumptions

In this study, a list assumption was made for the operation process and economic evaluation. Equipment purchased cost is taken from developed models in SuperPro Designer V9.0 and indexed to 2018 dollars. The method to calculate project investment expenditure are adopted from Peter et al. (2003) which commonly accurate within 30%. Addition to that, 3.02 installation factor is used because it is a common assumption factor for biorenewable facilities plant (Brown & Brown, 2014). Discounted cash flow analysis spreadsheet is used to estimate the MSE price ($/gal) with a zero of net present value (NPV) and a predetermined internal rate of return. The main assumptions are listed below, and the detailed values provided in Appendix A

- Plant capacity: 2000 Mg/day
- Plant feedstock: FW with 78% moisture content
- Plant distance: 12 mi radius (Poliafico & Murphy, 2007)
- Plant life: 20 y
- Equity financed: 100%
- The internal rate of return (IRR): 10% (Short et al., 1995)
- General plant depreciate: 7 y with 200% double declining balance (DDB)
- CHP plant depreciate: 20 y with 150% double declining balance (DDB)
- CHP feedstock: bio compost with 40% moisture content

- Contingency factor: 20% from total installed equipment and indirect cost
- Construction period: 2.5 years with total capital investment spent with 8%, 60% and 32% for first, second and third year respectively.
- Startup period: 6 months with considering 50% of revenues, 75% variable cost and 100% fixed expenses will be achieved.
- Utility prices and the number of operators per each equipment are listed in Table A-3 and Table A-4, Appendix A respectively.

Economies of scale will be performed to evaluate the reduction of the product value as increasing daily feedstock volume from 10 Mg to 5000 Mg. From this analysis, the range of optimum feedstock value with the lower MSE value will be estimated for the future study.

Sensitivity analysis

Further analysis is required to identify which parameter has the most significant impact on MSE value. A sensitivity analysis is a method by modifying one parameter value while maintained others. Table 6-1 shows the sensitivity analysis parameters selected for this analysis. These parameters are identified as a powerful impact on plant economic performance.

Results and discussions

Economic analysis

This plant is designed to have a feedstock capacity at 2000 Mg /day of FW. The mass and energy balance is obtained from the simulation result. From the discounted cash flow analysis, the MSE price was estimated to $1.88 per gallon with yielding an NPV of zero and

10% IRR. Detailed of discounted cash flow analysis for CHP integrated with fermentation process are shown in Table A-8, Appendix A. Results from this analysis reveals that integrated process is found to be the most economical process compared to the other studies from the previous chapter.

As detailed in Table B-5, Appendix B, this plant has a value for total installed equipment cost (TIEC) and total project investment (TPI) of $221 MM and $400 MM respectively. Addition to that, the annual utility cost ($/y) without credit power and heat from CHP was $30 MM annually as detailed in Figure 6-3. However, this value reduces more than 50% by using energy generated from CHP. This finding shows that fermentation process integrated with CHP have a significant impact on reducing the product cost.

Economies of scale for this study is represented in Figure 6-4. From the graph, there is a power relationship of -0.557 between MSE and feedstock size. It also shows that with the feedstock rate varying between 10 and 4000 Mg per day, the MSE of ethanol ranges from $74.16 to $0.10 per gallon of ethanol. The MSE keep decreasing because it considered there is surplus electricity that more than demand. Thus, it will be sold to the grid. However, higher feedstock capacity is impossible due to the logistic problem. As discussed in the previous chapter, FW is organic materials that easily to contaminate by other organisms. Therefore, proper storage is required in a loading area. Therefore it will incur the cost of operation and not economically viable.

Sensitivity analysis

Figure 6-4 shows the sensitivity analysis for this study. From the tornado chart, it indicates that feedstock plant capacity is the most influential parameter in estimating the

MSE value. The increasing the amount of FW feedstock to the plant from 1000 Mg/day to 3000 Mg/day will decrease the value of MSE from \$5.44 to \$0.27 per gallon.

Conclusions

This techno-economic analysis evaluates the cost of integrated CHP with FW fermentation process in producing ethanol as the primary product. From the discussions above, waste stream can be converted into heat and power energy and utilized back to the process. This process could save the annual utilities cost up to 50%. The results from discounted cash flow analysis showed that the MSE value for an integrated system is lower than a conventional plant as discussed in chapter 4, given by \$1.88 per gallon and \$2.41 per gallon respectively. This finding would justify that integrated CHP with ethanol production plant is more economically attractive and more energy efficient.

Additionally, from the sensitivity analysis, results showed that the variability of feedstock plant capacity at ±100% would given MSE value in the range of \$0.27 to \$5.44 per gallon. Based on the economics of scale, the graph shows that the MSE value is decreasing when the feedstock plant capacity increase. As expected, it occurs because of surplus electricity which will be sold to the grid to improve profitability. However, a higher amount of feedstock will require an extensive storage facility which not being modeled in this study. Therefore, further optimization study is recommended to be done to find the optimal feedstock plant including the storage facilities. This information is one of the essential aspects of the investor and shareholder for future consideration.

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Figures

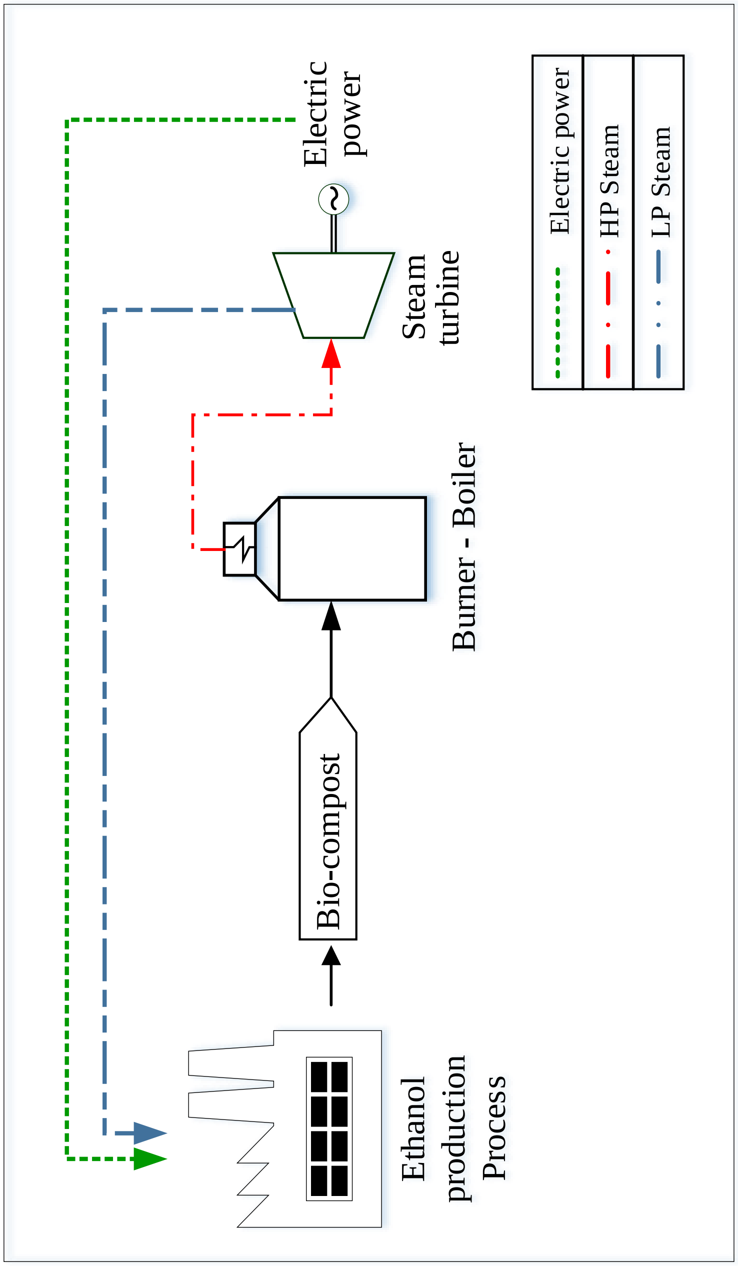

Figure 6-1 Combined heat power schematic diagram.

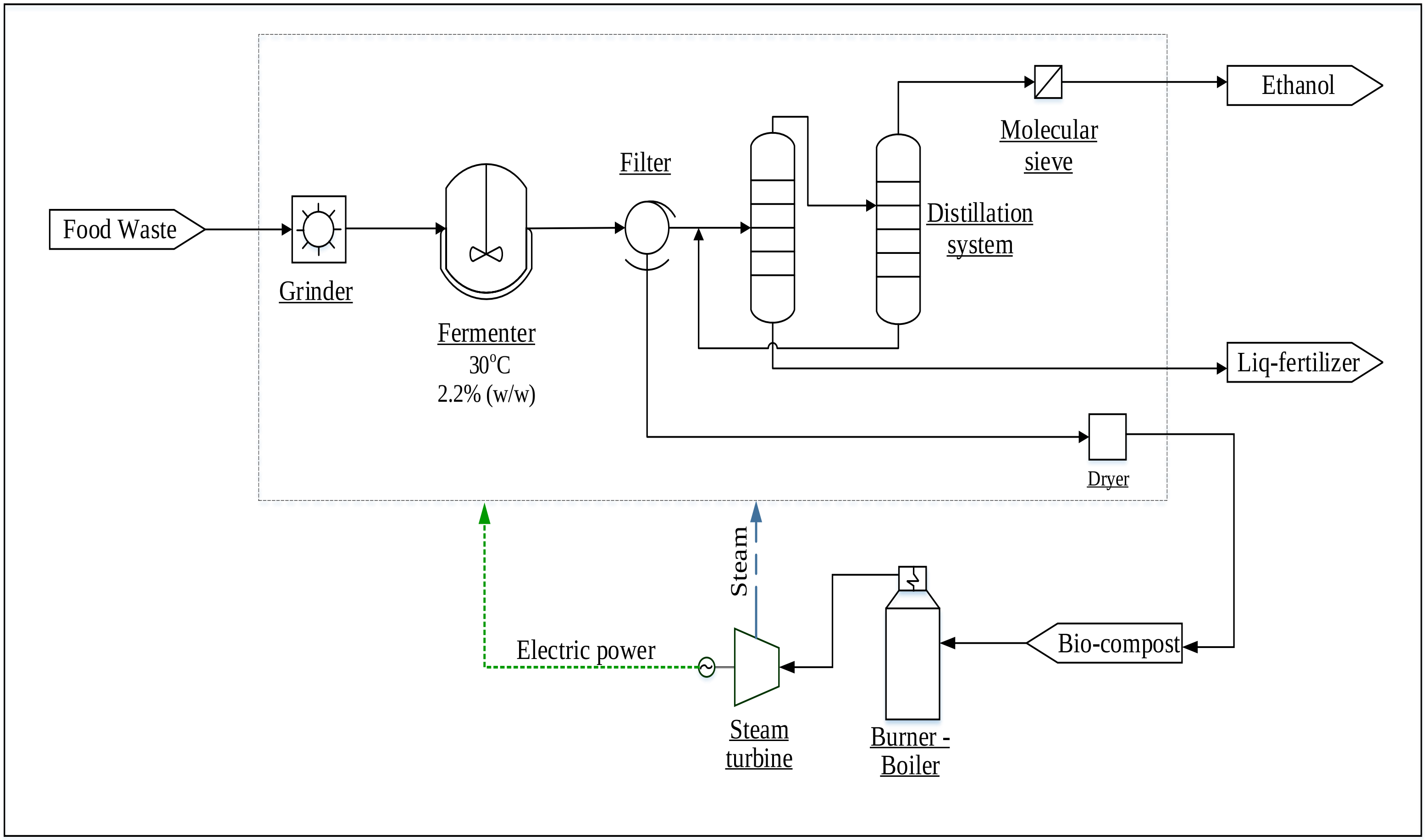

Figure 6-2 Process flow diagram of FW fermentation integrated with CHP.

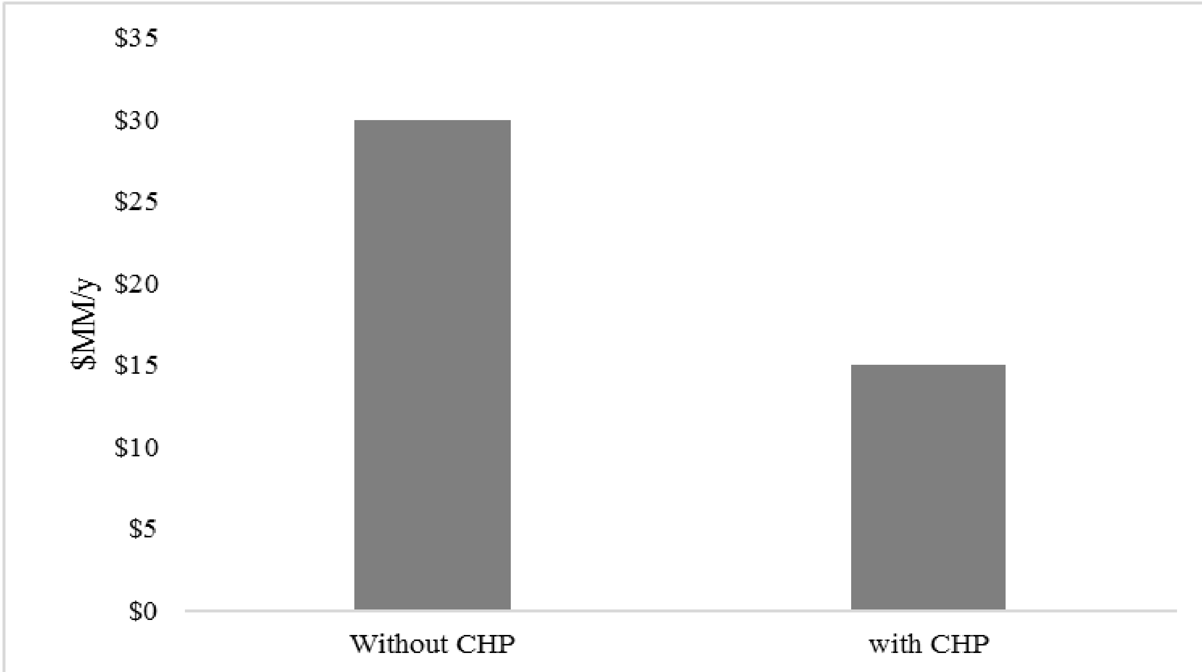

Figure 6-3 Annual utility cost.

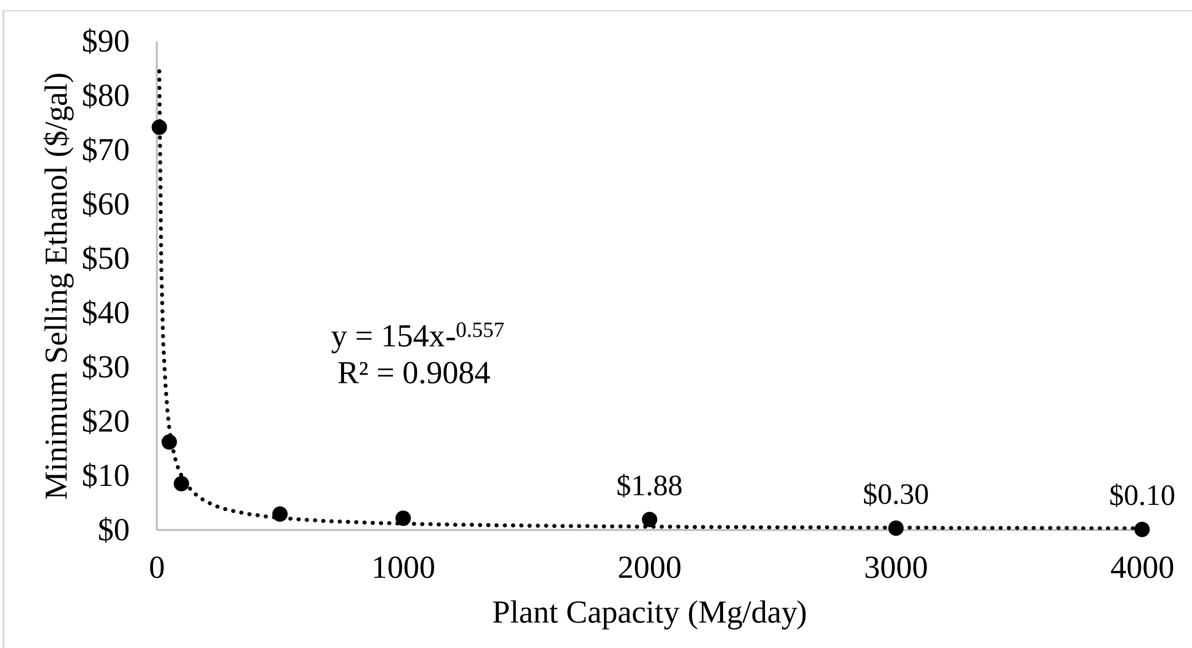

Figure 6-4 Economies of scale for FW fermentation process integrated with CHP.

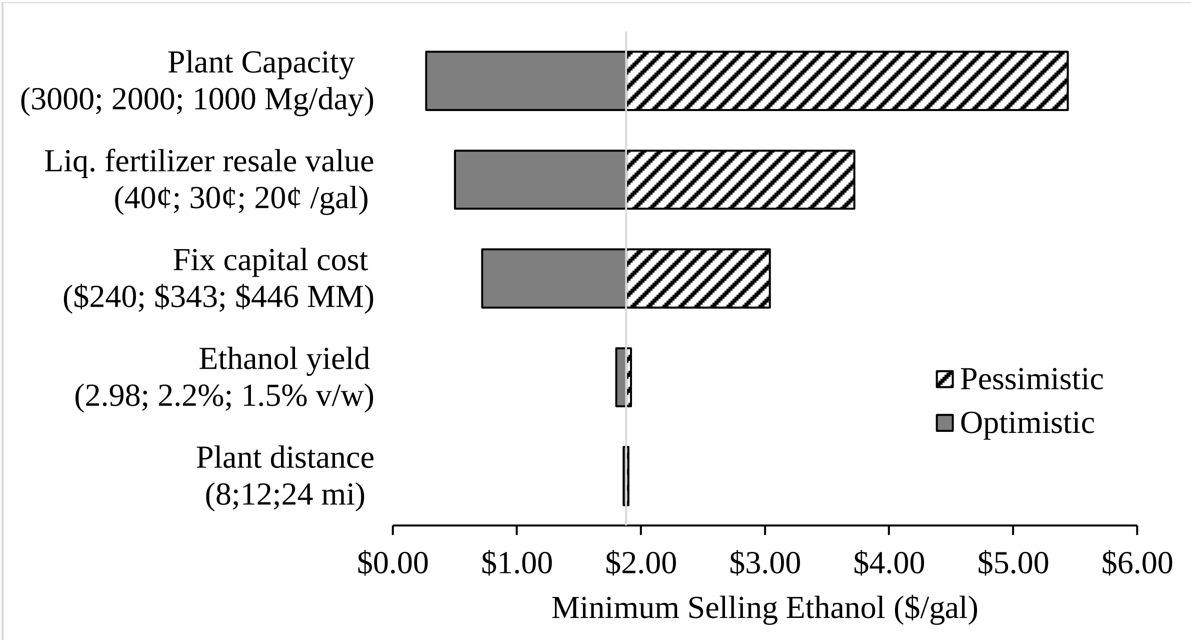

Figure 6-5 Sensitivity analysis of FW fermentation process integrated with CHP. (Optimistic is the best case scenario simulation, pessimistic is the worst case scenario simulation).

Tables

Table 6-1 Sensitivity analysis parameters for FW fermentation process integrated with CHP.

Parameters	Optimistic	Base case	Pessimistic
Plant distance (mi radius)	8	12	24
Plant Capacity (Mg/day)	1000	2000	3000
Liq. fertilizer resale value (¢/gal)	40	30	20
Ethanol yield (% w/w) wet basis	2.9	2.2	1.5
Fix capital cost ($MM)	407	585	757

CHAPTER 7. COMPARISON OF GLOBAL WARMING POTENTIAL IMPACT OF FOOD WASTE FERMENTATION PLANT WITH LANDFILLS DISPOSAL METHOD

Modified from paper will be submitted to the *Biochemical Engineering* journal.

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Abstract

Food waste (FW) has been identified as a critical global issue. The generation of FW is challenging to control because it is driven by various factors. Landfills, the most common final destinations for FW, are often associated with negative economic and environmental impact. Most previous studies have found that FW could also contribute to global warming due to GHG emission from decomposition of organic waste, so it is important to divert FW from landfills and find a better option such as using it to produce other value-added products. Depending on the particular FW composition, such waste has potential to be used in fermentation technology, so the primary objective of this study is to compare the global-warming potential (GWP) impact of FW fermentation and landfill disposal methods. Life-cycle analysis (LCA) was conducted to determine the effect on environmental of four scenarios: (i) FW fermentation without enzymes and a 2-step distillation system, (ii) FW fermentation without enzymes and a membrane distillation separation process, (iii) FW fermentation integrated with combined heat power (CHP), and (iv) FW in landfills. As expected, all FW fermentation options produced lower GWP impact values than a landfilling

method. From the overall fermentation process, the lowest average GWP value was 164.1 kg CO_2-eq/1 Mg of FW for the second scenario, revealing that membrane distillation is an environmentally-sound process, and suggesting that FW can be utilized to produce value-added products in fermentation while minimizing the environmental burden.

Introduction

The increasing volume of food waste (FW) every year is one of the most critical global issues. Gustavsson, et al., (2011) reported that about 1.3 billion tonnes of FW are produced yearly, equivalent to one-third of the world's food produced in any of the food supply chain stages. The increasing use of FW generation is driven by the modernization of the food system, and by cultural socio-demographic human behavior and attitudes, and safety policy (Thyberg & Tonjes, 2016). There are, however, negative economic, environment, social, and health impacts associated with FW if it is not managed effectively. For example, in 2015, FW economic losses accounted for approximately $940 billion in the United Kingdom and $1,500 to $1,100 per capita on average in the United States (FAO, 2015; Brian Lipinski, et al., 2015).

There are several disposal methods for FW, such as composting, anaerobic digestion (AD), incineration, landfills, and fermentation. While composting and anaerobic digestion is a mature technology that can produce bio-fertilizer and methane as primary products, this method is often deemed unfavorable because of its requirements of longer process time, higher cost of operation, ease spreading pathogens, and emission of volatile organic compounds (VOC) (Parthiba Karthikeyan, et al., 2018; Xu, Li, Ge, Yang, & Li, 2018). Incineration technology involves combustion and conversion of chemical energy into heat and electrical power, and even though itcould reduce the FW by up to 80-85%, it has still not received full support from some countries, mainly because toxic air emission exhaust from incineration is harmful to the environment. In addition, due to a the high moisture content of FW, its combustion efficiency will be affected and perhaps economically infeasible (Pham, et al., 2015). Landfill is a traditional method in waste management, and as reported by the EPA (2018a), in the year 2015 at least 76.1% of FW was sent to landfills. This disposal option will require large land space and high cost and it negatively impacts the environment (M.-H. Kim & Kim, 2010; Xu, et al., 2018). According to Gao, et al. (2017), landfill impact on climate change is ten times greater than that of anaerobic digestion, incineration, and composting, so this method will significantly add to global environmental problems.

Alternatively, FW can be used as a fermentation feedstock because it contains valuable resources for producing other valuable products. For example, glucose is found to be a significant components in FW, and yeast could convert glucose into ethanol under anaerobic conditions in a controlled environment. As discussed in Chapter 3, FW has potential for use in a fermentable process without enzymes in producing value-added products. Chapters 3, 4, and 5 comprehensively compares the economic impact of a FW fermentation plant for different scenarios. However, to determine feasibility of such new technology for commercialization, both economic and environmental perspectives should be considered.

Therefore, the main focus of this study is to make a comparative assessment of the global-warming potential (GWP) of FW fermentation and landfilling disposal methods, using life-cycle assessment (LCA) tools will to estimate GWP in terms of kg CO2 equivalents.

Methodology

Lifecycle assessment (LCA)

LCA is an essential tool for determining the environmental burden associated with FW fermentation processes, and concepts and life-cycle stages should be considered, as shown in Figure 7-1.

The LCA framework used in this study complies with ISO 14040: 2006. This framework includes the goal and scope of LCA, life-cycle inventory analysis (LCI), and life-cycle impact assessment (LCIA) and interpretation (ISO, 2006). Greenhouse emission release from the process should be assessed using the GWP in 100 years. This method, used in various studies to address global warming impact, includes three main commonly-used GHGs: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), that trap heat like a blanket and insulate the earth, thereby increasing global temperature and consequently leading to various catastrophic impacts on the ecosystem (Mendelsohn, et al., 2016). The GWP values relative to kg CO_2-eq/1 Mg of FW listed in Table 7-1 will be used to modify the GHG value through multiplication with a conversion factor taken from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) (Stoker, et al., 2013).

In this study, energy demand for a process plant is counted as an input stream for heating and steam production, assuming it is generated by natural gas fuel with 80% thermal efficiency. Emission generation will be estimated using a conversion factor of 66.33 kg CO_2-eq per 1mmBTU of steam or heat used in the plant (EPA, 2018b).

Since emission from electricity will also be included in this study, a few different electric power generation facilities are identified as possible electricity sources. Table 7-2 shows the conversion factors for an electric supply (Schlömer, et al., 2014), and their median value is used for estimating such emission.

For landfills, the number of emissions is estimated using The Landfill Gas Emission Model (LandGEM), version v3.02 (EPA, 2005) (EPA, 2010). The model for CH_4 generation is given by Equation 7-1.

$$A = \left[\sum_{x=S}^{T-1}\left\{W_x L'_x\left(e^{-k(T-x-1)} - e^{-k(T-x)}\right)\right\}\right]$$

Equation 7-1

Where:

A	= CH_4 generation (Mg/yr)
x	= Year in which FW was disposed
S	= Inventory year for the year which emissions are calculated (2017)
T	= Inventory year for the year which emission are calculated (2018)
W_x	= Quantity of FW disposed at the landfill (Mg) for one year
L’	= CH_4 generation potential (Mg CH_4/Mg FW) = MCF x DOC x DOC_F x F x 16/12 = L_o x 16/0.02367 x 10^{-6}
L_o	= CH_4 generation potential (m3 CH_4/Mg FW) = 493 x DOC
MCF	= CH_4 correction factor (fraction), assumed to be 1 for managed landfills
DOC	= degradable organic carbon (Mg C in FW / Mg FW)
DOC_F	= fraction of DOC decomposed, assumed to be 0.5
F	= fraction by volume of CH_4 in landfill gas assumed to be 0.5
k	= decay rate constant (yr^{-1})

For the amount of CO_2 emission in the landfills, Equation 7-2 will be used as follows;

$$B = A \times \left(\frac{1-F}{F} + OX\right) \times \frac{44}{16}$$

Equation 7-2

Where:

B	= CO_2 generation (Mg/yr)
A	= CH_4 generation from Equation 7-2 (Mg CH_4/yr)
F	= Fraction by volume of CH_4 in landfill gas assumed to be 0.5
OX	= Soil oxidation fraction, assumed to be 0.1
44	= Molecular weight of CO_2 (kg/kg-mol)
16	= Molecular weight of CH_4 (kg/kg-mol)

Goal and scope

The goal of this study is to evaluate the GWP for FW fermentation under assumptions of three different scenarios and compare the results with those of landfilling methods, to provide information on this process to investors or decision makers for future use. Scenarios (i) to (iv) will be modeled using SuperPro Designer V9.0 to estimate the overall mass and energy balance. The scenarios are listed below:

Scenario (i) : FW fermentation without enzymes and 2-step distillation system.

Scenario (ii) : FW fermentation without enzymes and membrane distillation.

Scenario (iii) : FW fermentation integrated with Combined Heat Power (CHP).

Scenario (iv) : FW in the landfill.

Functional unit

The functional unit in this study is the feedstock flow to the system boundary, and for calculation, 1 Mg of FW will be considered as a primary reference for each scenario.

System boundary

In this study, the gate-to-gate life cycle inventory will be considered. For each of the scenarios, system boundary is covered from the feedstock stream to its final product. The schematic flow for each scenario is shown in Figure 7-2 to 7-5. For scenario (i) to (iii), the system boundary is modeled with three main unit operations: size reduction, fermentation, and separation. Combined heat and power unit is integrated only modeled in scenario (iii) to determine the effect of in-site energy production by recycling solid waste stream.

In this study, the LCA scope is estimation of how many kgs of CO_2- eq will be released to the atmosphere from each scenario. Limitations and assumptions are as follows:

1. Transportation emission is not included because distance between the processing plant and collected areas are considered to be similar for all scenarios.
2. Equipment and chemical inputs for the fermentation process are not included.
3. Products and co-products will not be considered
4. GWP value for FW ahead of the system boundary will not be included, and it is assumed that such an amount will be the same for 1Mg of FW in all scenarios.

As mentioned above, Equation 7-3 will be used to calculate the total GWP impact for the respective scenarios

$$Total\ GWP\ impact\ (kg\ CO_{2\text{-}eq}) = Emissions\ (CO_2 \& CH_4) +$$
$$\sum energy\ generation\ [steam\ (mmBTU) + electric\ power\ (kWh)]$$

Equation 7-3

Results and discussions

Life-cycle inventory

Three scenarios were modeled using SuperPro designer V9.0 assuming 1 Mg of FW as feedstock, with the processes requiring heat and electrical energy as inputs. From Chapter 3, ethanol conversion from FW without enzymes is 2.2% (w/w) on a wet basis, and even though this conversion rate is low compared to the yield found by Uncu and Cekmecelioglu (2011), the economic impact is considerable. The FW composition used in this model is assumed to be 78% moisture content with 45% glucose, 19% starch, 5% fiber, and other trace elements. The energy demand and emission emited from the overall process were obtained from simulation.

GWP impacts

A summary of process energy input and estimated emission output is given in Table 7.3 for each scenario, and to estimate the GWP impact value, energy and emission impact will be included in the overall process. However, the GWP impact for electrical energy differs for different types of electricity sources. In this study, coal had a significantly higher impact on the environment followed by biomass co-firing and natural gas.

Figure 7-6 shows the overall value of GWP for each scenario. Scenario D, representing the landfilling method, produces a higher GWP impact of 2555.0 kg CO_2-eq/1 Mg of FW. From previous studies, the GWP values from the landfilling method range from 1010 kg CO_2-eq to 2538 kg CO_2-eq per FW(Kim & Kim, 2010; Parthiba Karthikeyan, et al., 2018), depending on FW compositions, duration, and location. For scenario (i), (ii), and (iii), while the GWP value also varies depending on the electric source, as a general assumption the average value reflects the environmental impact for all process plants. Scenario (ii) produced the smallest average value of GWP, followed by scenario (i) and (iii),viz., 164.1 kg CO_2-eq, 223.3 kg CO_2-eq, and 353.6 kg CO_2-eq per 1 Mg of FW, respectively.

Scenario (iii) has the highest amount of emission due to the combustion process and dryer used in a CHP system, and the burning associated with the solid waste process will add more CO_2 emission from fermentation. The solid-waste drying process also contributes to the higher amount of GWP because of its higher electric power requirement.

Scenario (ii) has a lower GWP impact than scenario (i) because of the small amount of steam requirement in the processing plant. The previous chapter discussed the distillation column being energy intensive compared to membrane distillation. In a distillation column, the process of separating ethanol from the fermentation broth largely depends on using more heating elements. In contrast, membrane distillation is driven by pressure differences and membrane selectivity, so both the energy input and the GWP impact are less in membrane distillation.

Conclusions

This study presents a comprehensive comparison of global warming potential impact for four different FW disposal option processes. The first three processes assumed use of fermentation technology to utilize the FW, while the fourth process reflected use of landfilling as a common disposal option. As expected, landfilling had a considerably higher GWP impact than the other fermentation processes, with results from the fermentation technology analysis shows that the lowest GWP impact was 164.1 kg CO_2-eq/ 1 Mg of FW for membrane separation, followed by distillation and CHP. This finding reveals that the less energy required in the conversion process, the less impact on the environment.

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Figures

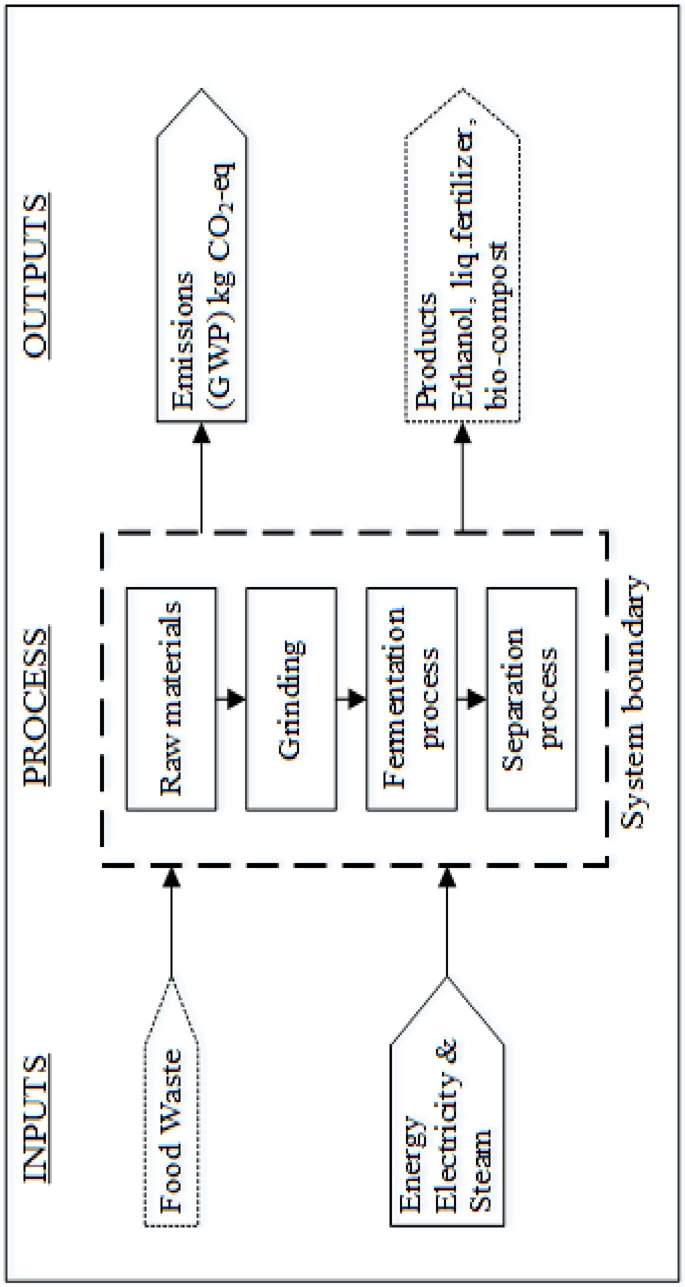

Figure 7-1 Lifecycles stages.

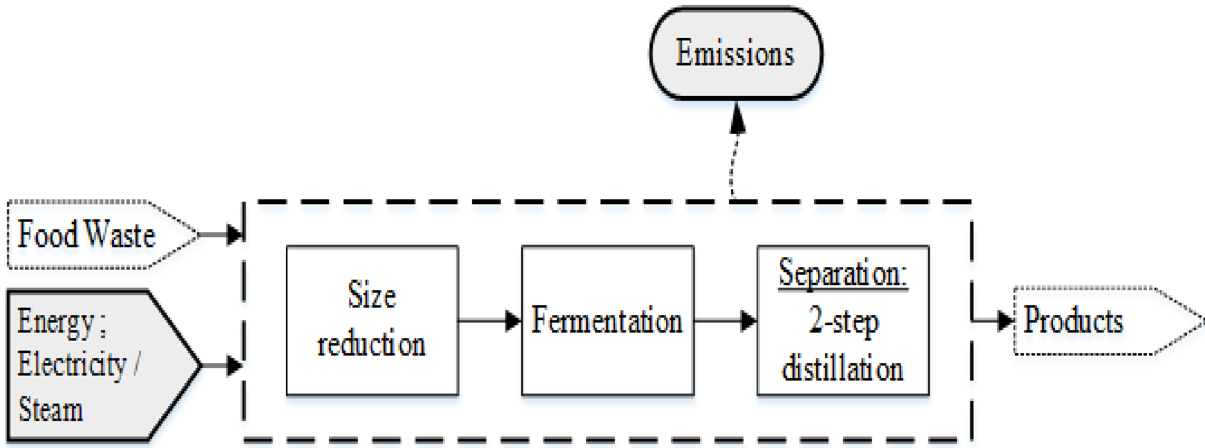

Figure 7-2 System boundary of scenario (i).

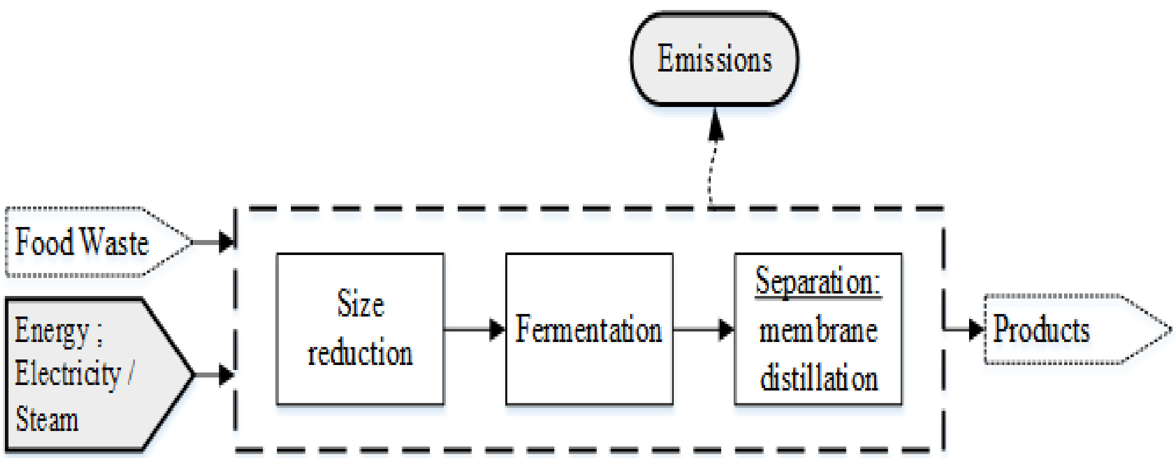

Figure 7-3 System boundary of scenario (ii).

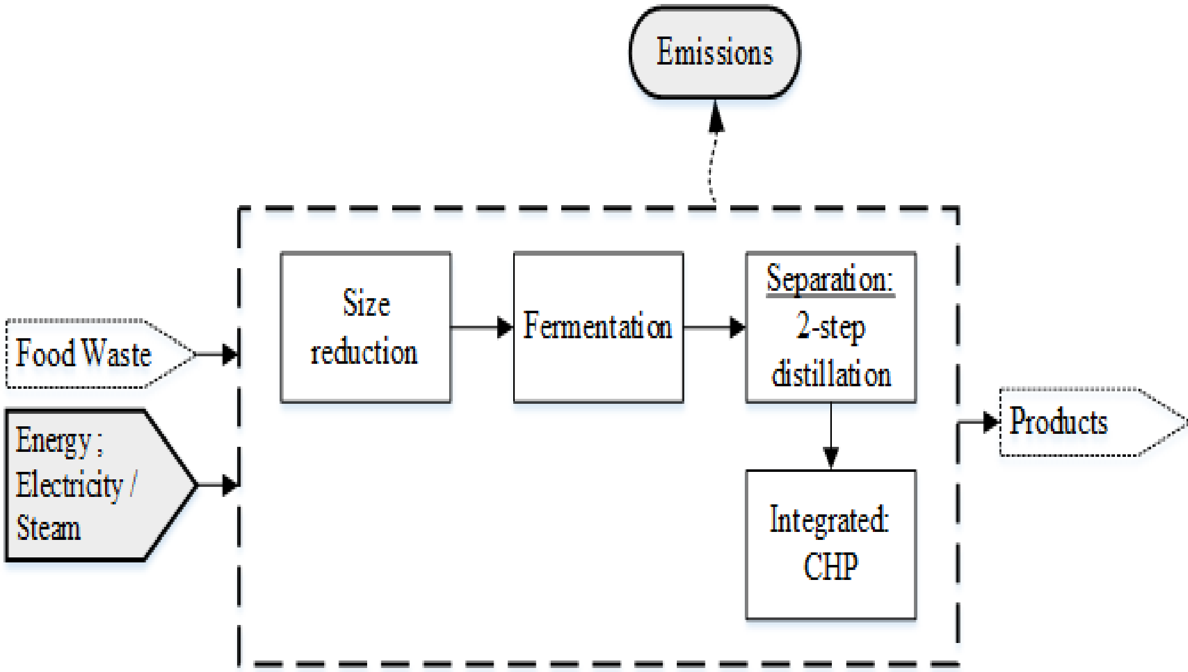

Figure 7-4 System boundary of scenario (iii).

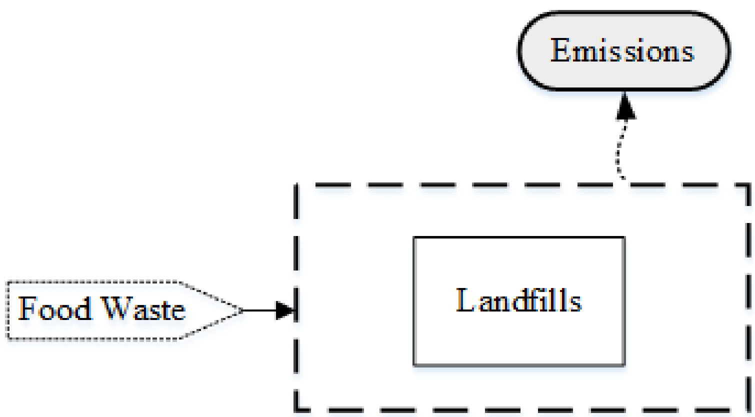

Figure 7-5 System boundary of scenario (iv).

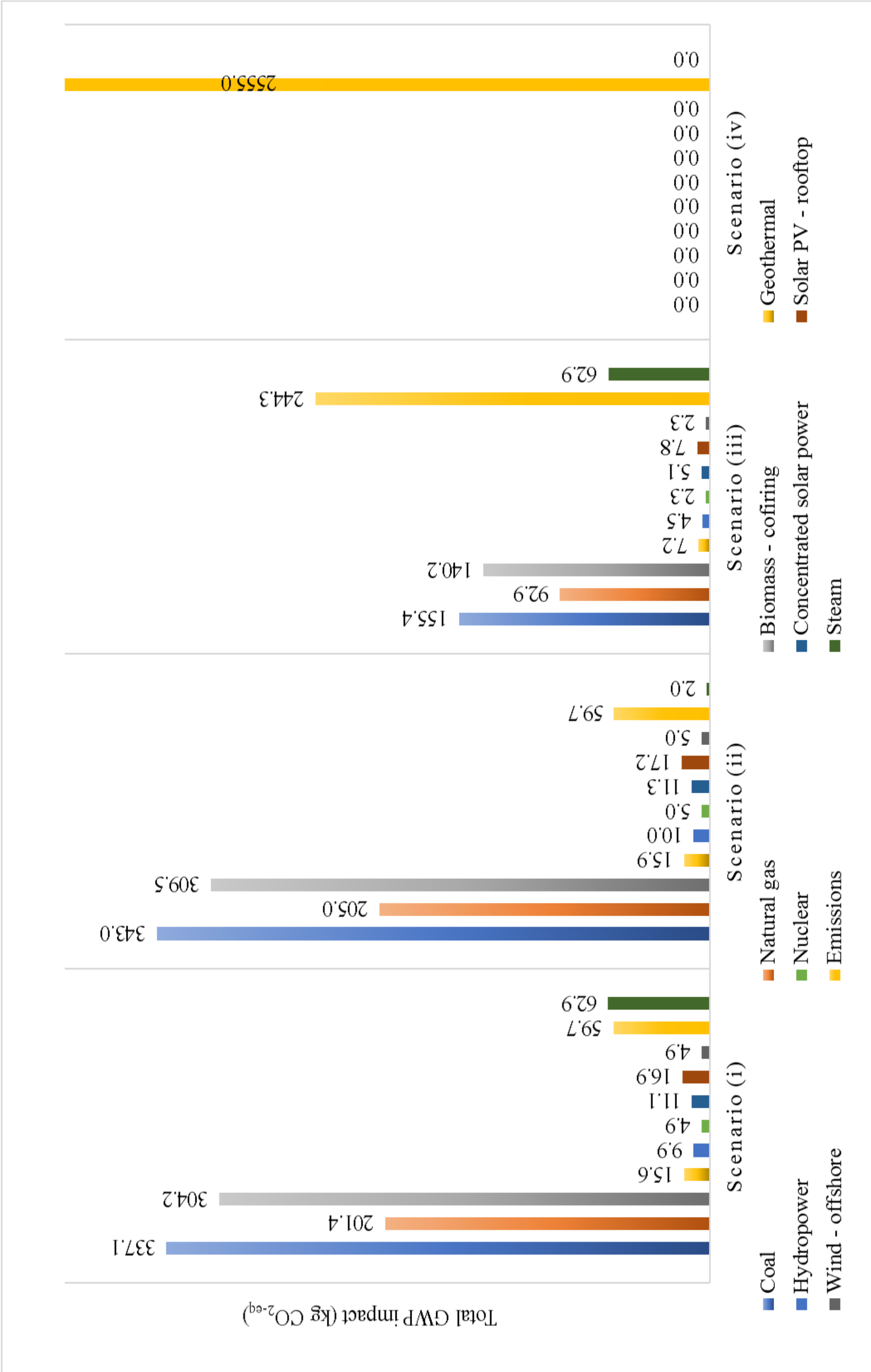

Figure 7-6 Overall GWP impact for all scenarios.

Tables

Table 7-1 Global warming potential (GWP) values relative to CO_2-eq (Stoker et al., 2013).

Industrial designation or common name	**Chemical formula**	**Approximately lifetime (y)**	**GWP values for 100-year time horizon (kg CO_2-eq)**
Carbon dioxide	CO_2	Variable	1
Methane	CH_4	12	28
Nitrous oxide	N_2O	114	265

Table 7-2 Emission of the selected source of electricity supply technology (Schlömer et al., 2014).

Source of electric power generation facilities	**GWP value (g CO_2-eq/kWh)**
Coal	820
Natural gas	490
Biomass – cofiring	740
Geothermal	38
Hydropower	24
Nuclear	12
Concentrated solar power	27
Solar PV – rooftop	41
Wind - offshore	12

Table 7-3 Summary of process energy input and emission output.

	Energy		**Emission**	
	Steam (mmBTU)	**Electric power (kWh)**	**CO_2 (kg)**	**CH_4 (kg)**
Scenario (i)	0.949	411.1	59.7	0
Scenario (ii)	0.03	418.3	59.7	0
Scenario (iii)	0.9481	193	244.3	0
Scenario (iv)	0	0	2981.4	35.2

CHAPTER 8. CONCLUSIONS AND FUTURE WORK

Overall conclusions

The main focus of this study is to make a comparative assessment of the economic and environmental impacts of FW fermentation in producing value-added products. Techno-economic analysis (TEA) and life cycle assessment (LCA) were conducted to estimate the impacts of the minimum selling ethanol price (MSE) and global warming potential (GWP). These methods provided a comprehensive comparative analysis of fermentation technologies for different scenarios depending upon assumptions.

This research study began with experiments on the lab scale. The FW fermentation was carried out over 18 combinations of the independent variables to determine the significant parameters in producing ethanol. The statistical test revealed that the higher yield ethanol from FW fermentation was 2.2% (w/w) wet basis at a pH of 5.0, temperature of 30^{o}C and agitation of 150 rpm. This finding is important to support that FW has the potential to be utilized in the fermentation process without enzymatic assistance in producing a valuable product.

TEA is a detailed study of the process and economic performance of FW fermentation in producing three value-added products: ethanol, liquid fertilizer and energy. The study was conducted on five scenarios: (a) fermentation with hydrolysis enzymes and a 2-step distillation system, (b) fermentation without enzymes and a 2-step distillation system, (c) fermentation without enzymes and a 1-step distillation system, (d) fermentation without enzymes and membrane distillation, and (e) fermentation without enzymes integrated with combined heat power (CHP). All studies were performed at 2000 Mg/day of feedstock capacity with 7900 operational hours. The MSE for each scenario was estimated using discounted cash flow analysis. From the analysis, the MSE value was found to be in the range of \$1.88 to \$6.24 per gallon depending upon assumptions. Results showed that the lowest and highest MSE values are given by the integrated CHP process (scenario e) and the fermentation without enzymes and membrane distillation (scenario d) respectively. This result may be explained by the fact that FW fermentation without enzymes is a potential approach to economically produce a valuable product.

The LCA is a method to assess the environmental impact of the FW fermentation process in comparison to the landfilling method. It was used to determine the GWP impact, i.e., how much the greenhouse gasses will be released from the process which given value by kg CO_2-eq. The functional unit is defined as 1 Mg of FW. From the analysis, landfilling had a higher value of GWP given by the average value of 2555 kg CO_2-eq/1 Mg of FW. The other FW fermentation process had a GWP impact in a range of 86%-93% reduction over the landfilling method. The results from this analysis indicate that the membrane distillation system had the least GWP impact value compared to the distillation column and the CHP integrated system.

Overall, the comprehensive comparison of the economic and environmental effect on FW fermentation will provide general information and understanding to a decision maker such as government agency or investor. Although the scenario from TEA differs from LCA, however, the fermentation approach is considered as a practical and sustainable way to manage FW rather than sending it to the landfills. This is one of the opportunities to convert waste into cost-effective value-added products while minimizing the environmental burden. Figure 8-1 shows the general research flow including results from TEA and LCA study.

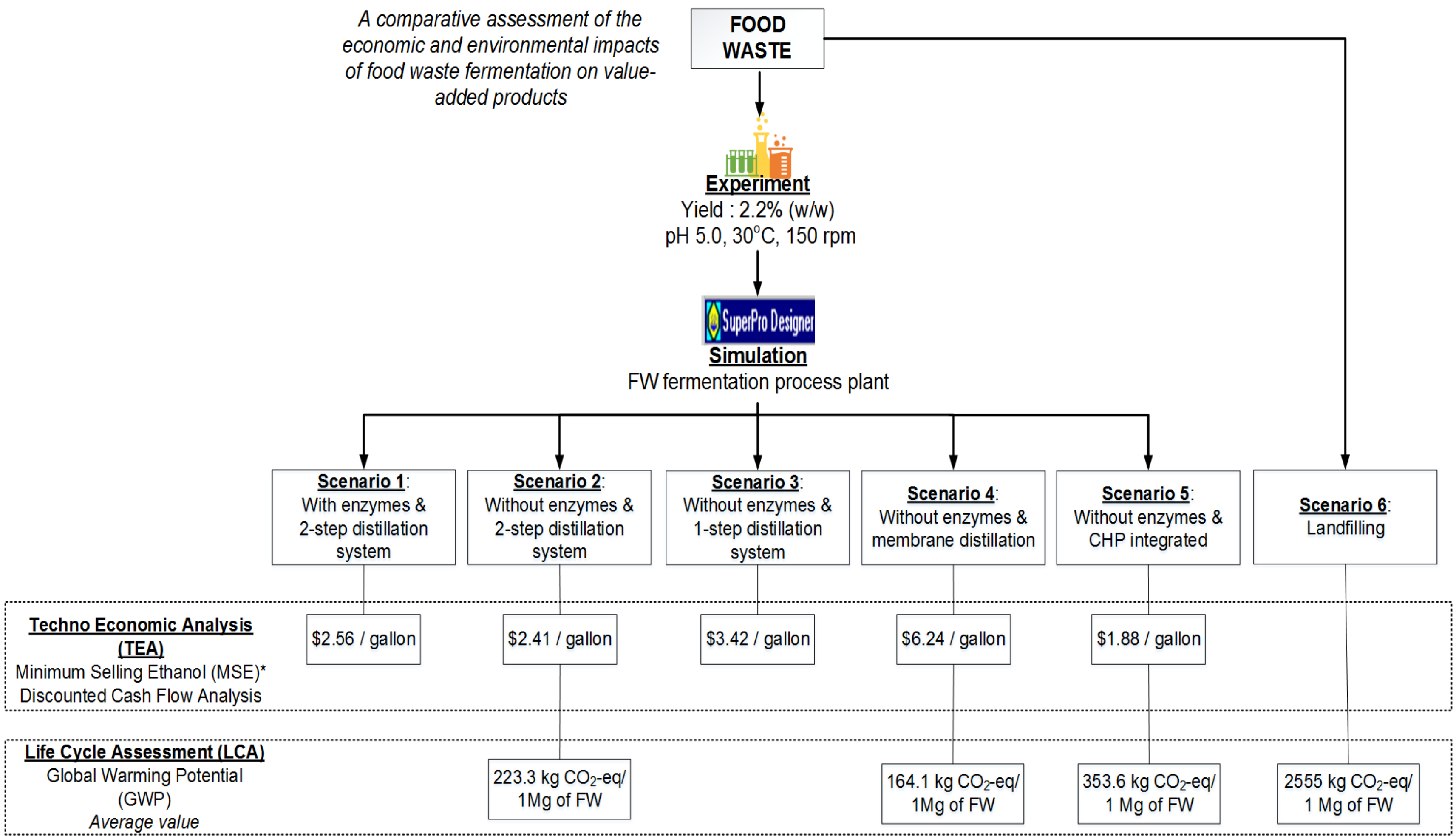

Figure 8-1 Overall research flow and results.

Future works

The approached employed in this study showed that FW is a potential substrate can be utilized and convert into valuable products. Ethanol is one of the products that has been applied mainly in transportation fuel. The volatility price of ethanol always being influenced by various factors such as political issues, market demand, gasoline price, subsidies, and government policy. Thus, it is difficult to maintain plant profitability.

FW is nutrient-rich resources that have the potential to be converted into other valuable product such as enzymes, organic acid, and chemicals through the different fermentation process. At present, there is no extensive TEA and LCA study available on the commercial plant for bio-product as mentioned above. Thus, a comprehensive comparison of economic and environmental impact to the various products from FW fermentation process could be interesting future work.

APPENDIX A. DISCOUNTED CASH FLOW ANALYSIS

Table A-1 Minimum selling ethanol (MSE) price per gallon for all studies.

Studies	MSE ($/gal)
1. FW fermentation process with hydrolysis enzymes and 2-step distillation system.	$2.56
2. FW fermentation process without enzymes and 2-step distillation system.	$2.41
3. FW fermentation process without enzymes and 1-step distillation system.	$3.42
4. FW fermentation process without enzymes and membrane distillation.	$6.24
5. Combined heat process integrated with FW fermentation process.	$1.88

Table A-2 Parameter assumption for discounted cash flow analysis.

Parameters	Assumption
Equity	100%
Loan interest	8%
Loan term years	10
Annual loan payment	0
Salvage value	0
Type of depreciation	DDB
General plant	200
Depreciation period (year)	7
Steam plant	150
Depreciation period (year)	20
Capital outlays	
% spend in year-1	8%
%spend in year-2	60%
% spend in year-3	32%
Start-up (year)	0.5
Revenues (% of normal)	50%
Variable cost (% of normal)	75%
Fix operating cost (% of normal)	100%
The internal rate of return	10%
Income tax rate	39%

Table A-3 Utility cost (EIA 2017).

Utility component	**Prices**
Enzymes (¢/gal ethanol)	3.35
Electricity (¢ /Kwh)	5.5
Water (¢/gal)	0.350
Steam ($/Mg)	12.00
Cooling water ($/Mg)	0.05
Chilled water ($/Mg)	0.40

Table A-4 Operator requirements for various types of process equipment (Brown & Brown, 2014).

Generic equipment type	**Operators per unit per shift**
Boilers	1
Electric generating plants	3
Crushers, mills, grinders	1
Evaporators	0.2
Furnace	0.5
Heat exchangers	0.1
Reactors/bioreactors	0.5
Clarifiers and thickeners	0.2
Centrifugal separators and filters	0.2
Mixers	0.3
Rotary and belt filters	0.2
Screens	0.05

Table A-5 Detailed discounted cash flow analysis for FW fermentation process with hydrolysis enzymes and 2-step distillation system.

Year		-2	-1	0	1	2	3	4	5	6	7	8	9	10
Fixed Capital Investment		$ 43,485,062.88	$ 281,190,621.60	$ 149,968,331.52										
Working Capital				$ 70,297,655.40										
Loan Payment					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Loan Interest Payment		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Loan Principal		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Sales														
Products Sales					$ 54,857,993.13	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61
Plant performance					1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Total Annual Sales					$ 54,857,993.13	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61
Annual Manufacturing Cost														
FeedStock					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Utilities					$ 16,544,250.00	$ 44,118,000.00	$ 44,118,000.00	$ 44,118,000.00	$ 44,118,000.00	$ 44,118,000.00	$ 44,118,000.00	$ 44,118,000.00	$ 44,118,000.00	$ 44,118,000.00
Transportation					$ 9,231,750.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00
Raw materials					$ 579,851.97	$ 1,546,271.91	$ 1,546,271.91	$ 1,546,271.91	$ 1,546,271.91	$ 1,546,271.91	$ 1,546,271.91	$ 1,546,271.91	$ 1,546,271.91	$ 1,546,271.91
Fixed Operating Cost					$ 4,847,938.85	$ 9,695,877.70	$ 9,695,877.70	$ 9,695,877.70	$ 9,695,877.70	$ 9,695,877.70	$ 9,695,877.70	$ 9,695,877.70	$ 9,695,877.70	$ 9,695,877.70
Total Product Cost					$ 31,203,790.82	$ 79,978,149.61	$ 79,978,149.61	$ 79,978,149.61	$ 79,978,149.61	$ 79,978,149.61	$ 79,978,149.61	$ 79,978,149.61	$ 79,978,149.61	$ 79,978,149.61
Annual Depreciation														
DDB					$ 19,147,742.33	$ 128,429,512.48	$ 91,735,366.06	$ 65,525,261.47	$ 46,803,758.19	$ 33,431,255.85	$ 23,879,468.47			
SL					$ 66,950,148.00	$ 66,950,148.00	$ 64,214,756.24	$ 57,334,603.78	$ 54,604,384.56	$ 54,604,384.56	$ 54,604,384.56			
Remaining Value					$ 449,503,293.67	$ 321,073,781.19	$ 229,338,415.14	$ 163,813,153.67	$ 117,009,395.48	$ 83,578,139.63	$ 59,698,671.16			
Actual					$ 66,950,148.00	$ 128,429,512.48	$ 91,735,366.06	$ 65,525,261.47	$ 54,604,384.56	$ 54,604,384.56	$ 54,604,384.56			
Net Revenue					$ (43,295,945.68)	$ (51,771,753.48)	$ (15,077,607.06)	$ 11,132,497.53	$ 22,053,374.44	$ 22,053,374.44	$ 22,053,374.44	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00
Losses Forward					$ -	$ (43,295,945.68)	$ (95,067,699.16)	$ (110,145,306.22)	$ (99,012,808.68)	$ (76,959,434.24)	$ (54,906,059.80)	$ (32,852,685.36)	$ -	$ -
Taxable Income					$ (43,295,945.68)	$ (95,067,699.16)	$ (110,145,306.22)	$ (99,012,808.68)	$ (76,959,434.24)	$ (54,906,059.80)	$ (32,852,685.36)	$ 43,805,073.64	$ 76,657,759.00	$ 76,657,759.00
Income Tax					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 17,083,978.72	$ 29,896,526.01	$ 29,896,526.01
Annual Cash Income					$ 23,654,202.32	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 59,573,780.28	$ 46,761,232.99	$ 46,761,232.99
Discount Factor		1.21	1.10	1.00	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47	0.42	0.39
Annual Present Value	$ 501,445,642.82				$ 21,503,820.29	$ 63,353,519.83	$ 57,594,108.94	$ 52,358,280.86	$ 47,598,437.14	$ 43,271,306.49	$ 39,337,551.36	$ 27,791,608.17	$ 19,831,327.54	$ 18,028,479.58
Capital Investment with Interest		$ 52,616,926.08	$ 309,309,683.76	$ 149,968,331.52										
Net Present Value				$ -										
NPV of Income Tax	$ 103,000,021.51				$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 7,969,802.16	$ 12,679,045.48	$ 11,526,404.98
NPV of Fuel Income	$ 734,929,784.92				$ 21,327,237.43	$ 77,553,590.65	$ 70,503,264.23	$ 64,093,876.57	$ 58,267,160.52	$ 52,970,145.93	$ 48,154,678.12	$ 43,776,980.10	$ 39,797,254.64	$ 36,179,322.40

Table A-5 (continued)

11	12	13	14	15	16	17	18	19	20
									$ (70,297,655.40)
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61	$ 156,635,908.61
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 44,118,000.00	$ 44,118,000.00	$ 44,118,000.00	$ 44,118,000.00	$ 44,118,000.00	$ 44,118,000.00	$ 44,118,000.00	$ 44,118,000.00	$ 44,118,000.00	$ 44,118,000.00
$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00
$ 1,546,271.91	$ 1,546,271.91	$ 1,546,271.91	$ 1,546,271.91	$ 1,546,271.91	$ 1,546,271.91	$ 1,546,271.91	$ 1,546,271.91	$ 1,546,271.91	$ 1,546,271.91
$ 9,695,877.70	$ 9,695,877.70	$ 9,695,877.70	$ 9,695,877.70	$ 9,695,877.70	$ 9,695,877.70	$ 9,695,877.70	$ 9,695,877.70	$ 9,695,877.70	$ 9,695,877.70
$ 79,978,149.61	$ 79,978,149.61	$ 79,978,149.61	$ 79,978,149.61	$ 79,978,149.61	$ 79,978,149.61	$ 79,978,149.61	$ 79,978,149.61	$ 79,978,149.61	$ 79,978,149.61
$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00	$ 76,657,759.00
$ 29,896,526.01	$ 29,896,526.01	$ 29,896,526.01	$ 29,896,526.01	$ 29,896,526.01	$ 29,896,526.01	$ 29,896,526.01	$ 29,896,526.01	$ 29,896,526.01	$ 29,896,526.01
$ 46,761,232.99	$ 46,761,232.99	$ 46,761,232.99	$ 46,761,232.99	$ 46,761,232.99	$ 46,761,232.99	$ 46,761,232.99	$ 46,761,232.99	$ 46,761,232.99	$ 46,761,232.99
0.35	0.32	0.29	0.26	0.24	0.22	0.20	0.18	0.16	0.15
$ 16,389,526.90	$ 14,899,569.90	$ 13,545,063.55	$ 12,313,694.14	$ 11,194,267.40	$ 10,176,606.72	$ 9,251,460.66	$ 8,410,418.78	$ 7,645,835.25	$ 6,950,759.32
									$ (10,449,298.54)
$ 10,478,549.98	$ 9,525,954.53	$ 8,659,958.66	$ 7,872,689.69	$ 7,156,990.63	$ 6,506,355.12	$ 5,914,868.29	$ 5,377,152.99	$ 4,888,320.90	$ 4,443,928.09
$ 32,890,293.09	$ 29,900,266.45	$ 27,182,060.41	$ 24,710,964.01	$ 22,464,512.73	$ 20,422,284.30	$ 18,565,713.00	$ 16,877,920.91	$ 15,343,564.46	$ 13,948,694.97

Table A-6 Detailed discounted cash flow analysis for FW fermentation process without enzymes and 2-step distillation system.

Year		-2	-1	0	1	2	3	4	5	6	7	8	9	10
Fixed Capital Investment		$ 30,886,179.84	$ 199,721,548.80	$ 106,518,159.36										
Working Capital				$ 49,930,387.20										
Loan Payment					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Loan Interest Payment		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Loan Principal		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Sales														
Product s Sales					$ 48,978,939.47	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22
Plant performance					$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00
Total Annual Sales					$ 48,978,939.47	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22
Annual Manufacturing Cost														
FeedStock					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Utilities					$ 11,518,613.25	$ 30,716,302.00	$ 30,716,302.00	$ 30,716,302.00	$ 30,716,302.00	$ 30,716,302.00	$ 30,716,302.00	$ 30,716,302.00	$ 30,716,302.00	$ 30,716,302.00
Transportation					$ 9,231,750.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00
Raw materials					$ 118,875.00	$ 317,000.00	$ 317,000.00	$ 317,000.00	$ 317,000.00	$ 317,000.00	$ 317,000.00	$ 317,000.00	$ 317,000.00	$ 317,000.00
Fixed Operating Cost					$ 3,250,593.93	$ 6,501,187.85	$ 6,501,187.85	$ 6,501,187.85	$ 6,501,187.85	$ 6,501,187.85	$ 6,501,187.85	$ 6,501,187.85	$ 6,501,187.85	$ 6,501,187.85
Total Product Cost					$ 24,119,832.18	$ 62,152,489.85	$ 62,152,489.85	$ 62,152,489.85	$ 62,152,489.85	$ 62,152,489.85	$ 62,152,489.85	$ 62,152,489.85	$ 62,152,489.85	$ 62,152,489.85
Annual Depreciation														
DDB					$ 13,590,575.87	$ 91,222,477.75	$ 65,158,912.68	$ 46,542,080.49	$ 33,244,343.20	$ 23,745,959.43	$ 16,961,399.59			
SL					$ 47,552,749.71	$ 47,552,749.71	$ 45,611,238.88	$ 40,724,320.42	$ 38,785,067.07	$ 38,785,067.07	$ 38,785,067.07			
Reamining Value					$ 319,278,672.13	$ 228,056,194.38	$ 162,897,281.70	$ 116,355,201.21	$ 83,110,858.01	$ 59,364,898.58	$ 42,403,498.98			
Actual					$ 47,552,749.71	$ 91,222,477.75	$ 65,158,912.68	$ 46,542,080.49	$ 38,785,067.07	$ 38,785,067.07	$ 38,785,067.07			
Net Revenue					$ (22,693,642.42)	$ (37,925,942.39)	$ (11,862,377.32)	$ 6,754,454.88	$ 14,511,468.29	$ 14,511,468.29	$ 14,511,468.29	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36
Losses Forward					$ -	$ (22,693,642.42)	$ (60,619,584.81)	$ (72,481,962.13)	$ (65,727,507.25)	$ (51,216,038.96)	$ (36,704,570.67)	$ (22,193,102.38)	$ -	$ -
Taxable Income					$ (22,693,642.42)	$ (60,619,584.81)	$ (72,481,962.13)	$ (65,727,507.25)	$ (51,216,038.96)	$ (36,704,570.67)	$ (22,193,102.38)	$ 31,103,432.98	$ 53,296,535.36	$ 53,296,535.36
Income Tax					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 12,130,338.86	$ 20,785,648.79	$ 20,785,648.79
Annual Cash Income					$ 24,859,107.29	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 41,166,196.50	$ 32,510,886.57	$ 32,510,886.57
Discount Factor		1.21	1.10	1.00	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47	0.42	0.39
Annual Present Value	$ 356,162,306.74				$ 22,599,188.45	$ 44,046,723.44	$ 40,042,475.85	$ 36,402,250.78	$ 33,092,955.25	$ 30,084,504.77	$ 27,349,549.79	$ 19,204,334.48	$ 13,787,789.57	$ 12,534,354.15
Capital Investment with Interest		$ 37,372,277.61	$ 219,693,703.68	$ 106,518,159.36										
Net Present Value				$ -										
NPV of Income Tax	$ 71,728,935.77				$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 5,658,892.60	$ 8,815,144.15	$ 8,013,767.41
NPV of Fuel Income	$ 273,972,413.71				$ 7,950,521.04	$ 28,910,985.59	$ 26,282,714.17	$ 23,893,376.52	$ 21,721,251.38	$ 19,746,592.17	$ 17,951,447.42	$ 16,319,497.66	$ 14,835,906.96	$ 13,487,188.15

Table A-6 (continued)

11	12	13	14	15	16	17	18	19	20
									$ -
									$ (49,930,387.20)
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22
$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00
$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22	$ 115,449,025.22
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 30,716,302.00	$ 30,716,302.00	$ 30,716,302.00	$ 30,716,302.00	$ 30,716,302.00	$ 30,716,302.00	$ 30,716,302.00	$ 30,716,302.00	$ 30,716,302.00	$ 30,716,302.00
$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00
$ 317,000.00	$ 317,000.00	$ 317,000.00	$ 317,000.00	$ 317,000.00	$ 317,000.00	$ 317,000.00	$ 317,000.00	$ 317,000.00	$ 317,000.00
$ 6,501,187.85	$ 6,501,187.85	$ 6,501,187.85	$ 6,501,187.85	$ 6,501,187.85	$ 6,501,187.85	$ 6,501,187.85	$ 6,501,187.85	$ 6,501,187.85	$ 6,501,187.85
$ 62,152,489.85	$ 62,152,489.85	$ 62,152,489.85	$ 62,152,489.85	$ 62,152,489.85	$ 62,152,489.85	$ 62,152,489.85	$ 62,152,489.85	$ 62,152,489.85	$ 62,152,489.85
$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36	$ 53,296,535.36
$ 20,785,648.79	$ 20,785,648.79	$ 20,785,648.79	$ 20,785,648.79	$ 20,785,648.79	$ 20,785,648.79	$ 20,785,648.79	$ 20,785,648.79	$ 20,785,648.79	$ 20,785,648.79
$ 32,510,886.57	$ 32,510,886.57	$ 32,510,886.57	$ 32,510,886.57	$ 32,510,886.57	$ 32,510,886.57	$ 32,510,886.57	$ 32,510,886.57	$ 32,510,886.57	$ 32,510,886.57
0.35	0.32	0.29	0.26	0.24	0.22	0.20	0.18	0.16	0.15
$ 11,394,867.41	$ 10,358,970.37	$ 9,417,245.79	$ 8,561,132.54	$ 7,782,847.76	$ 7,075,316.15	$ 6,432,105.59	$ 5,847,368.72	$ 5,315,789.74	$ 4,832,536.13
									$ (7,421,833.90)
$ 7,285,243.10	$ 6,622,948.27	$ 6,020,862.06	$ 5,473,510.97	$ 4,975,919.06	$ 4,523,562.78	$ 4,112,329.80	$ 3,738,481.64	$ 3,398,619.67	$ 3,089,654.25
$ 12,261,080.13	$ 11,146,436.49	$ 10,133,124.08	$ 9,211,930.98	$ 8,374,482.71	$ 7,613,166.10	$ 6,921,060.09	$ 6,291,872.81	$ 5,719,884.37	$ 5,199,894.88

Table A-7 Detailed discounted cash flow analysis for FW fermentation process without enzymes and 1-step distillation system.

Year		-2	-1	0	1	2	3	4	5	6	7	8	9	10
Fixed Capital Investment		$ 35,728,253.76	$ 231,032,203.20	$ 123,217,175.04										
Working Capital				$ 57,758,050.80										
Loan Payment					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Loan Interest Payment		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Loan Principal		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Sales														
Products Sales					$ 49,560,819.45	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55
Plant performance					1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Total Annual Sales					$ 49,560,819.45	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55
Annual Manufacturing Cost														
FeedStock					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Utilities					$ 11,140,125.00	$ 29,707,000.00	$ 29,707,000.00	$ 29,707,000.00	$ 29,707,000.00	$ 29,707,000.00	$ 29,707,000.00	$ 29,707,000.00	$ 29,707,000.00	$ 29,707,000.00
Transportation					$ 9,231,750.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00
Raw materials					$ 169,886.25	$ 453,030.00	$ 453,030.00	$ 453,030.00	$ 453,030.00	$ 453,030.00	$ 453,030.00	$ 453,030.00	$ 453,030.00	$ 453,030.00
Fixed Operating Cost					$ 3,601,099.78	$ 7,202,199.56	$ 7,202,199.56	$ 7,202,199.56	$ 7,202,199.56	$ 7,202,199.56	$ 7,202,199.56	$ 7,202,199.56	$ 7,202,199.56	$ 7,202,199.56
Total Product Cost					$ 24,142,861.03	$ 61,980,229.56	$ 61,980,229.56	$ 61,980,229.56	$ 61,980,229.56	$ 61,980,229.56	$ 61,980,229.56	$ 61,980,229.56	$ 61,980,229.56	$ 61,980,229.56
Annual Depreciation														
DDB					$ 15,732,192.88	$ 105,520,422.60	$ 75,371,730.43	$ 53,836,950.31	$ 38,454,964.51	$ 27,467,831.79	$ 19,619,879.85			
SL					$ 55,007,667.43	$ 55,007,667.43	$ 52,760,211.30	$ 47,107,331.52	$ 44,864,125.26	$ 44,864,125.26	$ 44,864,125.26			
Remaining Value					$ 369,321,479.12	$ 263,801,056.51	$ 188,429,326.08	$ 134,592,375.77	$ 96,137,411.26	$ 68,669,579.47	$ 49,049,699.62			
Actual					$ 55,007,667.43	$ 105,520,422.60	$ 75,371,730.43	$ 53,836,950.31	$ 44,864,125.26	$ 44,864,125.26	$ 44,864,125.26			
Net Revenue					$ (29,589,709.01)	$ (43,391,316.61)	$ (13,242,624.44)	$ 8,292,155.68	$ 17,264,980.74	$ 17,264,980.74	$ 17,264,980.74	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99
Losses Forward					$ -	$ (29,589,709.01)	$ (72,981,025.62)	$ (86,223,650.06)	$ (77,931,494.38)	$ (60,666,513.64)	$ (43,401,532.91)	$ (26,136,552.17)	$ -	$ -
Taxable Income					$ (29,589,709.01)	$ (72,981,025.62)	$ (86,223,650.06)	$ (77,931,494.38)	$ (60,666,513.64)	$ (43,401,532.91)	$ (26,136,552.17)	$ 35,992,553.82	$ 62,129,105.99	$ 62,129,105.99
Income Tax					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 14,037,095.99	$ 24,230,351.34	$ 24,230,351.34
Annual Cash Income					$ 25,417,958.42	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 48,092,010.00	$ 37,898,754.66	$ 37,898,754.66
Discount Factor		1.21	1.10	1.00	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47	0.42	0.39
Annual Present Value	$ 411,998,419.39				$ 23,107,234.93	$ 51,346,368.59	$ 46,678,516.90	$ 42,435,015.36	$ 38,577,286.69	$ 35,070,260.63	$ 31,882,055.12	$ 22,435,277.60	$ 16,072,771.59	$ 14,611,610.54
Capital Investment with Interest		$ 43,231,187.05	$ 254,135,423.52	$ 123,217,175.04										
Net Present Value				$ -										
NPV of Income Tax	$ 83,567,912.80				$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 6,548,408.88	$ 10,276,034.29	$ 9,341,849.36
NPV of Fuel Income	$ 391,394,563.54				$ 11,358,043.93	$ 41,301,977.94	$ 37,547,252.67	$ 34,133,866.07	$ 31,030,787.33	$ 28,209,806.67	$ 25,645,278.79	$ 23,313,889.81	$ 21,194,445.28	$ 19,267,677.53

Table A-7 (continued)

11	12	13	14	15	16	17	18	19	20
									$ (57,758,050.80)
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55	$ 124,109,335.55
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 29,707,000.00	$ 29,707,000.00	$ 29,707,000.00	$ 29,707,000.00	$ 29,707,000.00	$ 29,707,000.00	$ 29,707,000.00	$ 29,707,000.00	$ 29,707,000.00	$ 29,707,000.00
$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00
$ 453,030.00	$ 453,030.00	$ 453,030.00	$ 453,030.00	$ 453,030.00	$ 453,030.00	$ 453,030.00	$ 453,030.00	$ 453,030.00	$ 453,030.00
$ 7,202,199.56	$ 7,202,199.56	$ 7,202,199.56	$ 7,202,199.56	$ 7,202,199.56	$ 7,202,199.56	$ 7,202,199.56	$ 7,202,199.56	$ 7,202,199.56	$ 7,202,199.56
$ 61,980,229.56	$ 61,980,229.56	$ 61,980,229.56	$ 61,980,229.56	$ 61,980,229.56	$ 61,980,229.56	$ 61,980,229.56	$ 61,980,229.56	$ 61,980,229.56	$ 61,980,229.56
$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99	$ 62,129,105.99
$ 24,230,351.34	$ 24,230,351.34	$ 24,230,351.34	$ 24,230,351.34	$ 24,230,351.34	$ 24,230,351.34	$ 24,230,351.34	$ 24,230,351.34	$ 24,230,351.34	$ 24,230,351.34
$ 37,898,754.66	$ 37,898,754.66	$ 37,898,754.66	$ 37,898,754.66	$ 37,898,754.66	$ 37,898,754.66	$ 37,898,754.66	$ 37,898,754.66	$ 37,898,754.66	$ 37,898,754.66
0.35	0.32	0.29	0.26	0.24	0.22	0.20	0.18	0.16	0.15
$ 13,283,282.30	$ 12,075,711.19	$ 10,977,919.26	$ 9,979,926.60	$ 9,072,660.55	$ 8,247,873.22	$ 7,498,066.57	$ 6,816,424.15	$ 6,196,749.23	$ 5,633,408.39
									$ (8,585,366.22)
$ 8,492,590.33	$ 7,720,536.66	$ 7,018,669.69	$ 6,380,608.81	$ 5,800,553.46	$ 5,273,230.42	$ 4,793,845.84	$ 4,358,041.67	$ 3,961,856.06	$ 3,601,687.33
$ 17,516,070.48	$ 15,923,700.43	$ 14,476,091.30	$ 13,160,083.00	$ 11,963,711.82	$ 10,876,101.66	$ 9,887,365.14	$ 8,988,513.77	$ 8,171,376.15	$ 7,428,523.77

Table A-8 Detailed discounted cash flow analysis for FW fermentation process without enzymes and membrane distillation

Year		-2	-1	0	1	2	3	4	5	6	7	8	9	10
Fixed Capital Investment		$ 54,059,086.56	$ 349,566,199.20	$ 186,435,306.24										
Working Capital				$ 87,391,549.80										
Loan Payment					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Loan Interest Payment		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Loan Principal		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Sales														
Products Sales					$ 51,131,144.28	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87
Plant performance					$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00
Total Annual Sales					$ 51,131,144.28	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87
Annual Manufacturing Cost														
FeedStock					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Utilities					$ 3,898,125.00	$ 10,395,000.00	$ 10,395,000.00	$ 10,395,000.00	$ 10,395,000.00	$ 10,395,000.00	$ 10,395,000.00	$ 10,395,000.00	$ 10,395,000.00	$ 10,395,000.00
Transportation					$ 9,231,750.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00
Raw materials					$ 3,503,250.00	$ 9,342,000.00	$ 9,342,000.00	$ 9,342,000.00	$ 9,342,000.00	$ 9,342,000.00	$ 9,342,000.00	$ 9,342,000.00	$ 9,342,000.00	$ 9,342,000.00
Fixed Operating Cost														
Total Product Cost					$ 5,322,964.99	$ 10,645,929.99	$ 10,645,929.99	$ 10,645,929.99	$ 10,645,929.99	$ 10,645,929.99	$ 10,645,929.99	$ 10,645,929.99	$ 10,645,929.99	$ 10,645,929.99
Annual Depreciation					$ 21,956,089.99	$ 55,000,929.99	$ 55,000,929.99	$ 55,000,929.99	$ 55,000,929.99	$ 55,000,929.99	$ 55,000,929.99	$ 55,000,929.99	$ 55,000,929.99	$ 55,000,929.99
DDB														
SL														
Remaining Value					$ 23,787,147.56	$ 159,663,766.98	$ 114,045,547.85	$ 81,461,105.60	$ 58,186,504.00	$ 41,561,788.57	$ 29,686,991.84			
Actual					$ 83,230,047.43	$ 83,230,047.43	$ 79,831,883.49	$ 71,278,467.40	$ 67,884,254.67	$ 67,884,254.67	$ 67,884,254.67			
Net Revenue					$ 558,823,184.44	$ 399,159,417.46	$ 285,113,869.61	$ 203,652,764.01	$ 145,466,260.01	$ 103,904,471.43	$ 74,217,479.60			
Losses Forward					$ 83,230,047.43	$ 159,663,766.98	$ 114,045,547.85	$ 81,461,105.60	$ 67,884,254.67	$ 67,884,254.67	$ 67,884,254.67			
Taxable Income					$ (54,054,993.15)	$ (64,333,163.10)	$ (18,714,943.96)	$ 13,869,498.28	$ 27,446,349.22	$ 27,446,349.22	$ 27,446,349.22	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89
Income Tax					$ -	$ (54,054,993.15)	$ (118,388,156.24)	$ (137,103,100.20)	$ (123,233,601.92)	$ (95,787,252.71)	$ (68,340,903.49)	$ (40,894,554.27)	$ -	$ -
Annual Cash Income					$ (54,054,993.15)	$ (118,388,156.24)	$ (137,103,100.20)	$ (123,233,601.92)	$ (95,787,252.71)	$ (68,340,903.49)	$ (40,894,554.27)	$ 54,436,049.61	$ 95,330,603.89	$ 95,330,603.89
Discount Factor					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 21,230,059.35	$ 37,178,935.52	$ 37,178,935.52
Annual Present Value					$ 29,175,054.28	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 74,100,544.54	$ 58,151,668.37	$ 58,151,668.37
Capital Investment with Interest		1.21	1.1	1	0.909090909	0.826446281	0.751314801	0.683013455	0.620921323	0.56447393	0.513158118	0.46650738	0.424097618	0.385543289
Net Present Value	$ 623,379,423.08				$ 26,522,776.62	$ 78,785,623.05	$ 71,623,293.68	$ 65,112,085.16	$ 59,192,804.69	$ 53,811,640.63	$ 48,919,673.30	$ 34,568,450.90	$ 24,661,984.06	$ 22,419,985.51
NPV of Income Tax		$ 65,411,494.74	$ 384,522,819.12	$ 186,435,306.24										
NPV of Fuel Income				$ -										
NPV of Income Tax	$ 128,082,338.82				$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 9,903,979.37	$ 15,767,498.01	$ 14,334,089.10
NPV of Fuel Income	$ 752,932,195.08				$ 21,849,656.96	$ 79,453,298.05	$ 72,230,270.95	$ 65,663,882.68	$ 59,694,438.80	$ 54,267,671.64	$ 49,334,246.95	$ 44,849,315.40	$ 40,772,104.91	$ 37,065,549.92

Table A-8 (continued)

11	12	13	14	15	16	17	18	19	20
									$ (87,391,549.80)
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87
$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00
$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87	$ 150,331,533.87
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 10,395,000.00	$ 10,395,000.00	$ 10,395,000.00	$ 10,395,000.00	$ 10,395,000.00	$ 10,395,000.00	$ 10,395,000.00	$ 10,395,000.00	$ 10,395,000.00	$ 10,395,000.00
$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00
$ 9,342,000.00	$ 9,342,000.00	$ 9,342,000.00	$ 9,342,000.00	$ 9,342,000.00	$ 9,342,000.00	$ 9,342,000.00	$ 9,342,000.00	$ 9,342,000.00	$ 9,342,000.00
$ 10,645,929.99	$ 10,645,929.99	$ 10,645,929.99	$ 10,645,929.99	$ 10,645,929.99	$ 10,645,929.99	$ 10,645,929.99	$ 10,645,929.99	$ 10,645,929.99	$ 10,645,929.99
$ 55,000,929.99	$ 55,000,929.99	$ 55,000,929.99	$ 55,000,929.99	$ 55,000,929.99	$ 55,000,929.99	$ 55,000,929.99	$ 55,000,929.99	$ 55,000,929.99	$ 55,000,929.99
$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89	$ 95,330,603.89
$ 37,178,935.52	$ 37,178,935.52	$ 37,178,935.52	$ 37,178,935.52	$ 37,178,935.52	$ 37,178,935.52	$ 37,178,935.52	$ 37,178,935.52	$ 37,178,935.52	$ 37,178,935.52
$ 58,151,668.37	$ 58,151,668.37	$ 58,151,668.37	$ 58,151,668.37	$ 58,151,668.37	$ 58,151,668.37	$ 58,151,668.37	$ 58,151,668.37	$ 58,151,668.37	$ 58,151,668.37
$ 0.35	$ 0.32	$ 0.29	$ 0.26	$ 0.24	$ 0.22	$ 0.20	$ 0.18	$ 0.16	$ 0.15
$ 20,381,805.01	$ 18,528,913.64	$ 16,844,466.95	$ 15,313,151.77	$ 13,921,047.07	$ 12,655,497.33	$ 11,504,997.57	$ 10,459,088.70	$ 9,508,262.46	$ 8,643,874.96
									$ (12,990,197.02)
$ 13,030,990.09	$ 11,846,354.62	$ 10,769,413.30	$ 9,790,375.72	$ 8,900,341.57	$ 8,091,219.61	$ 7,355,654.19	$ 6,686,958.35	$ 6,079,053.05	$ 5,526,411.86
$ 33,695,954.47	$ 30,632,685.89	$ 27,847,896.26	$ 25,316,269.33	$ 23,014,790.30	$ 20,922,536.63	$ 19,020,487.85	$ 17,291,352.59	$ 15,719,411.45	$ 14,290,374.04

Table A-9 Detailed discounted cash flow analysis for combined heat process integrated with FW fermentation process

Year		-2	-1	0	1	2	3	4	5	6	7	8	9	10
Fixed Capital Investment		$ 31,879,236.00	$ 206,143,020.00	$ 109,942,944.00										
Working Capital				$ 51,535,755.00										
Loan Payment					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Loan Interest Payment		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Loan Principal		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Sales														
Products Sales					$ 46,380,171.74	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06
Plant performance					$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00
Total Annual Sales					$ 46,380,171.74	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06
Annual Manufacturing Cost														
FeedStock					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Utilities					$ 5,700,581.60	$ 15,201,550.94	$ 15,201,550.94	$ 15,201,550.94	$ 15,201,550.94	$ 15,201,550.94	$ 15,201,550.94	$ 15,201,550.94	$ 15,201,550.94	$ 15,201,550.94
Transportation					$ 9,231,750.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00
Raw materials					$ 1,278,375.00	$ 3,409,000.00	$ 3,409,000.00	$ 3,409,000.00	$ 3,409,000.00	$ 3,409,000.00	$ 3,409,000.00	$ 3,409,000.00	$ 3,409,000.00	$ 3,409,000.00
Fixed Operating Cost					$ 4,209,731.69	$ 8,419,463.37	$ 8,419,463.37	$ 8,419,463.37	$ 8,419,463.37	$ 8,419,463.37	$ 8,419,463.37	$ 8,419,463.37	$ 8,419,463.37	$ 8,419,463.37
Total Product Cost					$ 20,420,438.29	$ 51,648,014.31	$ 51,648,014.31	$ 51,648,014.31	$ 51,648,014.31	$ 51,648,014.31	$ 51,648,014.31	$ 51,648,014.31	$ 51,648,014.31	$ 51,648,014.31
Annual Depreciation														
General Plant														
DDB					$ 13,695,746.51	$ 91,928,402.71	$ 65,663,144.79	$ 46,902,246.28	$ 33,501,604.49	$ 23,929,717.49	$ 17,092,655.35			
SL					$ 47,920,736.57	$ 47,920,736.57	$ 45,964,201.36	$ 41,039,465.50	$ 39,085,205.23	$ 39,085,205.23	$ 39,085,205.23			
Remaining Value					$ 321,749,409.49	$ 229,821,006.78	$ 164,157,861.98	$ 117,255,615.70	$ 83,754,011.22	$ 59,824,293.73	$ 42,731,638.38			
Actual					$ 47,920,736.57	$ 91,928,402.71	$ 65,663,144.79	$ 46,902,246.28	$ 39,085,205.23	$ 39,085,205.23	$ 39,085,205.23			
Steam Plant														
DDB					$ 22,855.91	$ 607,776.61	$ 562,193.36	$ 520,028.86	$ 481,026.70	$ 444,949.69	$ 411,578.47	$ 380,710.08	$ 352,156.82	$ 325,745.06
SL					$ 406,327.20	$ 406,327.20	$ 416,439.53	$ 407,865.77	$ 400,855.58	$ 395,510.84	$ 391,979.49	$ 390,471.88	$ 390,471.88	$ 390,471.88
Remaining Value					$ 8,103,688.10	$ 7,495,911.49	$ 6,933,718.13	$ 6,413,689.27	$ 5,932,662.57	$ 5,487,712.88	$ 5,076,134.41	$ 4,695,424.33	$ 4,343,267.51	$ 4,017,522.44
Actual					$ 406,327.20	$ 607,776.61	$ 562,193.36	$ 520,028.86	$ 481,026.70	$ 444,949.69	$ 411,578.47	$ 390,471.88	$ 390,471.88	$ 390,471.88
Net Revenue					$ (22,367,330.31)	$ (37,480,793.57)	$ (11,169,952.40)	$ 7,633,110.61	$ 15,489,153.82	$ 15,525,230.82	$ 15,558,602.05	$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87
Losses Forward					$ -	$ (22,367,330.31)	$ (59,848,123.88)	$ (71,018,076.29)	$ (63,384,965.68)	$ (47,895,811.86)	$ (32,370,581.03)	$ (16,811,978.98)	$ -	$ -
Taxable Income					$ (22,367,330.31)	$ (59,848,123.88)	$ (71,018,076.29)	$ (63,384,965.68)	$ (47,895,811.86)	$ (32,370,581.03)	$ (16,811,978.98)	$ 37,852,934.89	$ 54,664,913.87	$ 54,664,913.87
Income Tax					$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 14,762,644.61	$ 21,319,316.41	$ 21,319,316.41
Annual Cash Income					$ 25,959,733.46	$ 55,055,385.75	$ 55,055,385.75	$ 55,055,385.75	$ 55,055,385.75	$ 55,055,385.75	$ 55,055,385.75	$ 40,292,741.14	$ 33,736,069.34	$ 33,736,069.34
Discount Factor		1.21	1.1	1	0.909090909	0.826446281	0.751314801	0.683013455	0.620921323	0.56447393	0.513158118	0.46650738	0.424097618	0.385543289
Annual Present Value	$ 367,613,679.96				$ 23,599,757.69	$ 45,500,318.80	$ 41,363,926.18	$ 37,603,569.26	$ 34,185,062.96	$ 31,077,329.96	$ 28,252,118.15	$ 18,796,861.11	$ 14,307,386.66	$ 13,006,715.15
Capital Investment with Interest		$ 38,573,875.56	$ 226,757,322.00	$ 109,942,944.00										
Net Present Value				0										
NPV of Income Tax	$ 74,653,261.74				$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 6,886,882.66	$ 9,041,471.31	$ 8,219,519.38
NPV of Fuel Income	$ 218,396,942.16				$ 6,337,752.99	$ 23,046,374.50	$ 20,951,249.54	$ 19,046,590.49	$ 17,315,082.27	$ 15,740,983.88	$ 14,309,985.34	$ 13,009,077.59	$ 11,826,434.17	$ 10,751,303.79

Table A-9 (continued)

11	12	13	14	15	16	17	18	19	20
									$ (51,535,755.00)
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06
$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00	$ 1.00
$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06	$ 106,703,400.06
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 15,201,550.94	$ 15,201,550.94	$ 15,201,550.94	$ 15,201,550.94	$ 15,201,550.94	$ 15,201,550.94	$ 15,201,550.94	$ 15,201,550.94	$ 15,201,550.94	$ 15,201,550.94
$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00	$ 24,618,000.00
$ 3,409,000.00	$ 3,409,000.00	$ 3,409,000.00	$ 3,409,000.00	$ 3,409,000.00	$ 3,409,000.00	$ 3,409,000.00	$ 3,409,000.00	$ 3,409,000.00	$ 3,409,000.00
$ 8,419,463.37	$ 8,419,463.37	$ 8,419,463.37	$ 8,419,463.37	$ 8,419,463.37	$ 8,419,463.37	$ 8,419,463.37	$ 8,419,463.37	$ 8,419,463.37	$ 8,419,463.37
$ 51,648,014.31	$ 51,648,014.31	$ 51,648,014.31	$ 51,648,014.31	$ 51,648,014.31	$ 51,648,014.31	$ 51,648,014.31	$ 51,648,014.31	$ 51,648,014.31	$ 51,648,014.31
$ 301,314.18	$ 278,715.62	$ 257,811.95	$ 238,476.05	$ 220,590.35	$ 204,046.07	$ 188,742.62	$ 174,586.92	$ 161,492.90	$ 149,380.93
$ 390,471.88	$ 390,471.88	$ 390,471.88	$ 390,471.88	$ 390,471.88	$ 390,471.88	$ 390,471.88	$ 390,471.88	$ 390,471.88	$ 390,471.88
$ 3,716,208.26	$ 3,437,492.64	$ 3,179,680.69	$ 2,941,204.64	$ 2,720,614.29	$ 2,516,568.22	$ 2,327,825.60	$ 2,153,238.68	$ 1,991,745.78	$ 1,842,364.85
$ 390,471.88	$ 390,471.88	$ 390,471.88	$ 390,471.88	$ 390,471.88	$ 390,471.88	$ 390,471.88	$ 390,471.88	$ 390,471.88	$ 390,471.88
$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87	$ 54,664,913.87
$ 21,319,316.41	$ 21,319,316.41	$ 21,319,316.41	$ 21,319,316.41	$ 21,319,316.41	$ 21,319,316.41	$ 21,319,316.41	$ 21,319,316.41	$ 21,319,316.41	$ 21,319,316.41
$ 33,736,069.34	$ 33,736,069.34	$ 33,736,069.34	$ 33,736,069.34	$ 33,736,069.34	$ 33,736,069.34	$ 33,736,069.34	$ 33,736,069.34	$ 33,736,069.34	$ 33,736,069.34
0.350493899	0.318630818	0.28966438	0.263331254	0.239392049	0.217629136	0.197844669	0.17985879	0.163507991	0.148643628
$ 11,824,286.50	$ 10,749,351.36	$ 9,772,137.60	$ 8,883,761.45	$ 8,076,146.78	$ 7,341,951.62	$ 6,674,501.47	$ 6,067,728.61	$ 5,516,116.92	$ 5,014,651.74
									$ (7,660,461.60)
$ 7,472,290.34	$ 6,792,991.22	$ 6,175,446.56	$ 5,614,042.33	$ 5,103,674.85	$ 4,639,704.41	$ 4,217,913.10	$ 3,834,466.45	$ 3,485,878.59	$ 3,168,980.54
$ 9,773,912.54	$ 8,885,375.03	$ 8,077,613.67	$ 7,343,285.15	$ 6,675,713.77	$ 6,068,830.70	$ 5,517,118.82	$ 5,015,562.56	$ 4,559,602.33	$ 4,145,093.03

APPENDIX B. TOTAL CAPITAL INVESTMENT

Table B-1 Detailed investment for FW fermentation process with hydrolysis enzymes and 2-step distillation system.

Total Capital Investment (a)			
	2018 Dollars	Assumption (Peter, Timmerhaus & West, 2003 ; Brown & Brown, 2014)	
TPEC (Total Purchased Equipment)	**99,883,000.00**		
Purchased equipment installation	38,954,370.00	39% Percent of TPEC	
Instrumentation and control	25,969,580.00	26% Percent of TPEC	
Piping	30,963,730.00	31% Percent of TPEC	
Electrical systems	9,988,300.00	10% Percent of TPEC	
building (including services)	28,966,070.00	29% Percent of TPEC	
Yard improvements	11,985,960.00	12% Percent of TPEC	
services facilities	54,935,650.00	55% Percent of TPEC	
TIEC (Total Installed Equipment Cost)	**301,646,660.00**	3.02	
Indirect Cost			
Engineering	31,962,560.00	32% Percent of TPEC	
Construction	33,960,220.00	34% Percent of TPEC	
Legal and contractors fees	22,973,090.00	23% Percent of TPEC	
TIC (Total Indirect Cost)	88,895,870.00	3.91	
Project Contingency	78,108,506.00	78% Percent of TPEC	20% percent of TIC + TIEC
FCI (Fixed Capital Investment)	**468,651,036.00**	4.69	TIC + TIEC +Contingency
Non-depreiated Direct Costs			
Working Capital	70,297,655.40		15% percent of FCI
Land	5,992,980.00	6% Percent of TPEC	
TPI (total Project Investment)	**544,941,671.40**		FCI + WC + Land
Lang Factor	5.46		

Table B-2 Detailed investment for FW fermentation process without enzymes and 2-step distillation system.

Total Capital Investment (b)		
	2018 Dollars	Assumption (Peter, Timmerhaus & West, 2003 ; Brown & Brown, 2014)
TPEC (Total Purchased Equipment)	**70,944,000.00**	
Purchased equipment installation	27,668,160.00	39% Percent of TPEC
Instrumentation and control	18,445,440.00	26% Percent of TPEC
Piping	21,992,640.00	31% Percent of TPEC
Electrical systems	7,094,400.00	10% Percent of TPEC
building (including services)	20,573,760.00	29% Percent of TPEC
Yard improvements	8,513,280.00	12% Percent of TPEC
services facilities	39,019,200.00	55% Percent of TPEC
TIEC (Total Installed Equipment Cost)	**214,250,880.00**	3.02
Indirect Cost		
Engineering	22,702,080.00	32% Percent of TPEC
Construction	24,120,960.00	34% Percent of TPEC
Legal and contractors fees	16,317,120.00	23% Percent of TPEC
TIC (Total Indirect Cost)	63,140,160.00	3.91
Project Contingency	55,478,208.00	78% Percent of TPEC 20% percent of TIC + TIEC
FCI (Fixed Capital Investment)	**332,869,248.00**	4.69 TIC + TIEC +Contingency
Non-depreiated Direct Costs		
Working Capital	49,930,387.20	15% percent of FCI
Land	4,256,640.00	6% Percent of TPEC
TPI (total Project Investment)	**387,056,275.20**	FCI + WC + Land
Lang Factor	5.46	

Table B-3 Detailed investment for FW fermentation process without enzymes and 1-step distillation system.

Total Capital Investment (c)			
	2018 Dollars	Assumption (Peter, Timmerhaus & West, 2003 ; Brown & Brown, 2014)	
TPEC (Total Purchased Equipment)	**82,066,000.00**		
Purchased equipment installation	32,005,740.00	39% Percent of TPEC	
Instrumentation and control	21,337,160.00	26% Percent of TPEC	
Piping	25,440,460.00	31% Percent of TPEC	
Electrical systems	8,206,600.00	10% Percent of TPEC	
building (including services)	23,799,140.00	29% Percent of TPEC	
Yard improvements	9,847,920.00	12% Percent of TPEC	
services facilities	45,136,300.00	55% Percent of TPEC	
TIEC (Total Installed Equipment Cost)	**247,839,320.00**	3.02	
Indirect Cost			
Engineering	26,261,120.00	32% Percent of TPEC	
Construction	27,902,440.00	34% Percent of TPEC	
Legal and contractors fees	18,875,180.00	23% Percent of TPEC	
TIC (Total Indirect Cost)	73,038,740.00	3.91	
Project Contingency	64,175,612.00	78% Percent of TPEC	20% percent of TIC + TIEC
FCI (Fixed Capital Investment)	**385,053,672.00**	4.69	TIC + TIEC +Contingency
Non-depreiated Direct Costs			
Working Capital	57,758,050.80		15% percent of FCI
Land	4,923,960.00	6% Percent of TPEC	
TPI (total Project Investment)	**447,735,682.80**		FCI + WC + Land
Lang Factor	5.46		

Table B-4 Detailed investment of FW fermentation process without enzymes and membrane distillation

Total Capital Investment (d)			
	2018 Dollars	Assumption (Peter, Timmerhaus & West, 2003 ; Brown & Brown, 2014)	
TPEC (Total Purchased Equipment)	**124,171,000.00**		
Purchased equipment installation	48,426,690.00	39% Percent of TPEC	
Instrumentation and control	32,284,460.00	26% Percent of TPEC	
Piping	38,493,010.00	31% Percent of TPEC	
Electrical systems	12,417,100.00	10% Percent of TPEC	
building (including services)	36,009,590.00	29% Percent of TPEC	
Yard improvements	14,900,520.00	12% Percent of TPEC	
services facilities	68,294,050.00	55% Percent of TPEC	
TIEC (Total Installed Equipment Cost)	**374,996,420.00**	302%	
Indirect Cost			
Engineering	39,734,720.00	32% Percent of TPEC	
Construction	42,218,140.00	34% Percent of TPEC	
Legal and contractors fees	28,559,330.00	23% Percent of TPEC	
TIC (Total Indirect Cost)	110,512,190.00	3.91	
Project Contingency	97,101,722.00	78% Percent of TPEC	20% percent of TIC + TIEC
FCI (Fixed Capital Investment)	**582,610,332.00**	4.69	TIC + TIEC +Contingency
Non-depreiated Direct Costs			
Working Capital	87,391,549.80		15% percent of FCI
Land	7,450,260.00	6% Percent of TPEC	
TPI (total Project Investment)	**677,452,141.80**		FCI + WC + Land
Lang Factor	5.46		

Table B-5 Detailed investment of combined heat process integrated with FW fermentation process.

Total Capital Investment (e)					
	2018 Dollars	Assumption (Peter, Timmerhaus & West, 2003 ; Brown & Brown, 2014)			
TPEC (Total Purchased Equipment)	**73,225,000.00**				
Purchased equipment installation	28,557,750.00	39%	Percent of TPEC		
Instrumentation and control	19,038,500.00	26%	Percent of TPEC		
Piping	22,699,750.00	31%	Percent of TPEC		
Electrical systems	7,322,500.00	10%	Percent of TPEC		
building (including services)	21,235,250.00	29%	Percent of TPEC		
Yard improvements	8,787,000.00	12%	Percent of TPEC		
services facilities	40,273,750.00	55%	Percent of TPEC		
TIEC (Total Installed Equipment Cost)	**221,139,500.00**	302%			
Indirect Cost					
Engineering	23,432,000.00	32%	Percent of TPEC		
Construction	24,896,500.00	34%	Percent of TPEC		
Legal and contractors fees	16,841,750.00	23%	Percent of TPEC		
TIC (Total Indirect Cost)	65,170,250.00	3.91			
Project Contingency	57,261,950.00	78%	Percent of TPEC	20%	percent of TIC + TIEC
FCI (Fixed Capital Investment)	**343,571,700.00**	4.69			TIC + TIEC +Contingency
Non-depreiated Direct Costs					
Working Capital	51,535,755.00			15%	percent of FCI
Land	4,393,500.00	6%	Percent of TPEC		
TPI (total Project Investment)	**399,500,955.00**				FCI + WC + Land
Lang Factor	5.46				